

UNCLASSIFIED ~~CONFIDENTIAL~~

Copy 6
RM E55A24

NACA RM E55A24



RESEARCH MEMORANDUM

PERFORMANCE OF A TUBULAR TURBOJET COMBUSTOR AT HIGH
PRESSURES AND TEMPERATURES

By Helmut F. Butze and Jerrold D. Wear

Lewis Flight Propulsion Laboratory

Cleveland, Ohio
CLASSIFICATION CHANGED

UNCLASSIFIED

To _____

By authority of Mess TPA 7 *Effective*
Date 5-29-59
NB 7-6-59

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

April 5, 1955

~~CONFIDENTIAL~~
UNCLASSIFIED

CONFIDENTIAL
UNCLASSIFIED

ERRATA

NACA RM E55A24

PERFORMANCE OF A TUBULAR TURBOJET COMBUSTOR
AT HIGH PRESSURES AND TEMPERATURES
By Helmut F. Butze and Jerrold D. Wear

April 5, 1955

Please replace page 23 with the attached errata sheet.

UNCLASSIFIED

CONFIDENTIAL

UNCLASSIFIED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

NASA Technical Library



3 1176 01435 7991

PERFORMANCE OF A TUBULAR TURBOJET COMBUSTOR AT HIGH

PRESSURES AND TEMPERATURES

By Helmut F. Butze and Jerrold D. Wear

SUMMARY

The effects on combustor performance of operation at the high inlet-air pressures, temperatures, and velocities representative of conditions that may be encountered in high-pressure-ratio turbojet engines or at high flight speeds were studied in a single tubular combustor. Performance characteristics investigated were combustor-liner temperatures, carbon deposition, smoke formation, and combustion efficiency. Carbon-deposition and smoke-formation tests were conducted over a range of combustor-inlet pressures from 35 to 173 pounds per square inch absolute, combustor-inlet temperatures from 200° to 860° F, and reference velocities from 78 to 180 feet per second. Combustion efficiency and liner temperature tests were conducted at selected conditions within these ranges.

Although liner temperatures were affected to some extent by changes in velocity and fuel-air ratio, by far the most significant effects were produced by changes in inlet-air temperature. The increases in liner temperature were, generally, appreciably larger than the increases in inlet-air temperature. Liner temperatures as high as 2000° F were observed at an inlet-air temperature of 860° F. Operation of the combustor at high inlet-air pressures, temperatures, and velocities resulted in frequent liner failures due to extreme warping and burning of the liner.

At low inlet-air temperatures, carbon deposition increased rapidly with increasing pressure; the carbon was generally deposited uniformly in the dome and the upstream section of the liner. At high inlet-air temperatures, total carbon deposition was considerably lower at all pressure levels and was concentrated in one or more isolated places in the upstream section of the liner, while the dome and the rest of the liner were very clean. Smoke formation increased with increasing pressure, and with increasing inlet-air temperature up to a temperature of 600° F; further increases in inlet-air temperature reduced smoke formation.

UNCLASSIFIED

High values of combustion efficiency were observed at most of the conditions investigated. In general, combustion efficiency increased with increasing pressures and temperatures and with decreasing velocity. The effects of pressure and velocity were very small at high inlet-air temperatures.

INTRODUCTION

Research on problems associated with turbojet combustors designed for operation in high-speed, high-altitude aircraft is being conducted at the Lewis laboratory. A previous report (ref. 1) describes the effects of high inlet-air pressure (up to 12 atm) and velocity on combustion efficiency, carbon deposition, and smoke formation in a single tubular combustor. The investigation reported herein extends the data of reference 1 to include the effects of high inlet-air temperatures on these and other performance factors.

At supersonic flight speeds (Mach number, 2.5) and at a flight altitude of 50,000 feet, an engine with a pressure ratio of 7, representative of current development engines, will produce a combustor inlet-air temperature of 940° F and a pressure of 166 pounds per square inch absolute. Similar pressure and temperature conditions occur even at low flight speeds in higher pressure-ratio (12 to 15) engines. In contrast, a current-production engine with a pressure ratio of 4, operating at the same altitude but at subsonic flight speed, will produce a corresponding pressure and temperature of 13 pounds per square inch absolute and 290° F, respectively. Air-flow rates per unit cross-sectional area are also being increased in current development engines, resulting in higher velocities through the combustor.

Investigations have shown that high pressure will result in greater carbon deposition (ref. 1), in more smoke in the exhaust gases (ref. 2), and in higher flame emissivities (ref. 3). The high flame emissivities, in combination with less effective convective cooling resulting from high inlet-air temperatures, would be expected to increase liner wall temperatures and thus seriously affect liner life. Increases in velocity result in decreases in combustion efficiency, which will, however, be at least partly offset by the improved efficiency resulting from higher combustor-inlet pressures.

The effects of high inlet-air temperatures on these performance factors have not been investigated extensively, particularly in combination with high pressures and velocities. An investigation was undertaken therefore to determine the effects of high inlet-air pressures, temperatures, and velocities on combustor wall temperatures, carbon deposition, smoke formation, and combustion efficiency.

A single tubular combustor, installed in a direct-connect facility capable of supplying air at pressures and temperatures as high as 300 pounds per square inch absolute and 900° F, respectively, was used in this investigation. Combustion-chamber carbon-deposition and smoke-formation data were obtained at inlet-air pressures from 35 to 173 pounds per square inch absolute and inlet-air temperatures from 200° to 860° F over a wide range of inlet-air velocities and fuel-air ratios. Combustion efficiency tests were conducted at inlet-air pressures of 58 and 176 pounds per square inch absolute and temperatures of 200° and 860° F over a range of velocities and fuel-air ratios. In addition, a number of tests were conducted with a combustor liner that was instrumented to provide wall temperature data.

APPARATUS

Combustor Installation

The combustor installation, shown schematically in figures 1 and 2, was essentially the same as that described in reference 1. A production-model J33 inner liner and dome were installed in a high-pressure combustor housing similar to a J33 housing except that circular inlet- and exhaust-transition sections were used. This combustor assembly was connected to the laboratory 450-pound-per-square-inch air-supply system and to an atmospheric-exhaust muffler.

Air-flow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the combustor; fuel-flow rate was controlled by means of a needle valve located downstream of a high-pressure fuel pump. Four water-spray nozzles, spaced axially in the exhaust ducting and supplied by a high-capacity, high-pressure pump, were used to cool the exhaust gases prior to their passage through the exhaust control valve.

The combustion air was heated to the desired temperature by means of a preheater capable of heating 15 pounds per second of high-pressure air to a temperature of about 900° F. The heat exchanger consisted of a series of coiled Inconel tubes, connected in parallel, through which the high-pressure air flowed. The tubes were heated externally, in crossflow, by combustion gases from an auxiliary turbojet combustor.

Instrumentation

Air-flow rates were measured by a square-edged orifice plate installed according to A.S.M.E. specifications. The pressure drop across the orifice was measured by a commercial pneumatic differential-pressure transmitter and a differential manometer. Fuel flow was measured

by a calibrated rotameter located upstream of a high-pressure pump. Inlet-air and exhaust-gas temperatures were measured by two enclosed single-junction chromel-alumel thermocouples (plane C-C, fig. 2) and by eight two-junction platinum - platinum-rhodium (13 percent) thermocouple rakes (section B-B; fig. 2), respectively. The exhaust-gas thermocouple supports were made of brass and were cooled by a stream of high-pressure air bled from the combustion-air supply upstream of the orifice. Construction details of the temperature- and pressure-measuring probes are shown in reference 1. By means of a suitable switching arrangement, either individual temperatures or an instantaneous average of all exhaust-gas thermocouples could be obtained. Inlet-air and exhaust-gas total pressures were each measured by four three-point total-pressure probes located at plane D-D and section A-A (fig. 2), respectively, and connected to strain-gage-type pressure pickups. Individual pressure probes and thermocouple junctions were located at the centers of equal area. All combustor pressures and temperatures were indicated on automatic-balancing potentiometers.

The relative quantity of smoke in the exhaust gases was determined with a smoke meter that consisted essentially of an air-cooled filter press through which a metered volume of exhaust gas was drawn. Smoke particles suspended in the gas were deposited on a paper filter disk. The optical density of the smoke-covered filter paper, as determined by a transmission densitometer, was considered a measure of the amount of smoke in the sample. The apparatus and method of smoke determination are described more fully in reference 2. Exhaust-gas samples were obtained from one of the three-point total-pressure probes located at section A-A (fig. 2).

Liner Equipped with Thermocouples

Wall temperatures of the combustor inner liner were determined with a special liner equipped with chromel-alumel thermocouples. The thermocouple junctions were welded at selected locations to the outer surface of the liner and were covered with an insulating ceramic cement in order to minimize convection losses. A developed view of the liner showing thermocouple locations and designations is presented in figure 3(a); a photograph of the liner and dome showing the method of thermocouple installation is presented in figure 3(b). The original installation contained 16 thermocouples; the results from only 14 thermocouples are presented herein because two of the junctions failed in preliminary tests.

Fuel Nozzles

During the investigation four sizes of fuel nozzles were utilized in order to achieve the desired flow rates and still maintain an adequate nozzle pressure drop. The flow capacities of the four nozzles are listed in the following table:

Nominal flow capacity at pressure drop of 100 lb/sq in., gal/hr	Approximate spray angle at rated capacity, deg
21.5	80
40	80
60	70
^a 110	75

^aModified 60-gal/hr nozzle.

Fuel

A production-type jet fuel, MIL-F-5624B, grade JP-4 (NACA fuel 52-288), was used in this investigation; chemical and physical properties of this fuel are presented in table I.

PROCEDURE

Carbon Deposition and Smoke

Carbon-deposition and smoke-formation tests were conducted at the approximate combustor operating conditions shown in the following table:

Test condition	Inlet-air total pressure, lb/sq in. abs	Inlet-air temper- ature, °F	Inlet-air reference velocity, ^a ft/sec	Temperature rise, °F
A	35	200 - 860	78	1165
B	60	200 - 860	78	1165
C	86	200 - 860	78	1165
D	86	400	78 - 180	1165
E	86	400	78	765 - 1565
F	173	200 - 860	78	1165

^aBased on maximum cross-sectional area of combustor housing (0.267 sq ft at reference plane, fig. 2) and inlet-air static pressure and temperature.

An inlet-air temperature of 860° F and pressures of 35, 86, and 173 pounds per square inch absolute (conditions A, C, and F) are representative of operation in a turbojet engine with a pressure ratio of 12 (at sea-level and rated speed) at a flight Mach number of 1.8 and

altitudes of 70,000, 50,000, and 35,000 feet, respectively. The other test conditions were included to provide comparisons of the independent effects of pressure, temperature, velocity, and fuel-air ratio on carbon deposition and smoke.

Carbon-deposition tests were conducted for a period of 2 to 3 hours, during which time the specified operation conditions were held constant. Prior to each test run, the combustor inner-liner and dome assembly and the ignition plug were cleaned with rotating wire brushes and then weighed on a torsion-type balance; at the end of the test these parts were reweighed. The difference in weight of these parts plus the weight of the deposit on the fuel nozzle and any loose deposits within the chamber represented the total deposit reported herein. Since reference 1 shows that, for test durations up to 3 hours, carbon deposition increases linearly with time, the data have been generalized and are expressed as grams of carbon deposited per hour.

Smoke measurements were made by the aforementioned filter technique. A bypass line located immediately upstream of the smoke meter provided continuous purging of the sampling line and served to reduce the gas pressure at the smoke meter. After combustor operation had been stabilized at the desired conditions, a fixed volume of exhaust gas was passed through the smoke meter. The difference in optical density readings between the smoke-covered and clean filters was considered a measure of the amount of smoke in the sample and is referred to as "smoke density" in this report.

Combustion Efficiency and Liner Temperatures

Combustion efficiency tests were conducted over a range of fuel-air ratios at the combustor-inlet conditions shown in the following table:

Inlet-air total pressure, lb/sq in. abs	Inlet-air temperature, °F	Inlet-air reference velocity, ft/sec
58	200	70
		130
		170
	860	70
		130
		170
176	200	70
		130
		170
	860	70
		130
		170

Combustion efficiency is defined as the ratio of the actual enthalpy rise across the combustor (between plane C-C and section B-B, fig. 2) to the total enthalpy supplied by the fuel and was computed by the method of reference 4. The combustor-exit enthalpy was computed from the instantaneous average (parallel circuit) of the 16 exhaust-gas thermocouples. Temperatures were taken as total temperatures and no corrections for conduction and radiation errors were made.

Test conditions for the liner temperature tests were the same as those employed for the combustion efficiency tests. However, because of structural failure of the liner, wall temperature data were not obtained at all test conditions.

Pressure Drop

Combustor total-pressure loss data were recorded at all test conditions. Pressure drop is expressed herein as the dimensionless ratio $\Delta P/q_r$, where ΔP is the total-pressure loss across the combustor and q_r is the reference velocity pressure based on the reference velocity and static density of the inlet air.

RESULTS

The data obtained during this investigation are presented in table II. The effects of combustor operating variables on liner wall temperatures, carbon deposition, smoke formation, combustion efficiency, and combustor pressure loss are described, in this order, in the following paragraphs.

Liner Wall Temperatures

Temperatures of the outer surface of the combustor liner obtained under the various operating conditions are presented in figure 4. The data show that, at an inlet-air temperature of 860° F, liner temperatures generally increased with increasing exhaust-gas temperature. At an inlet-air temperature of 200° F, however, the increase in liner temperatures with increasing exhaust-gas temperature was less pronounced and in a few cases a decrease was noted. Increases in reference velocity, at constant inlet-air pressure and temperature, decreased liner wall temperatures. Comparisons of the curves representing constant inlet-air velocity and temperature but at different pressures indicate that inlet-air pressure had no consistent effect on liner temperature. The most pronounced effect was caused by increases in inlet-air temperature, which effected very large increases in liner wall temperatures. The increase in liner temperatures was, generally, considerably greater

than the increase in inlet-air temperature. Liner temperatures varied from approximately 200° to 1000° F at the low inlet-air temperature conditions and from about 1000° to 2000° F at an inlet-air temperature of 860° F.

In order to illustrate the effect of axial distance from the fuel nozzle on liner surface temperature, the data of figure 4 have been cross-plotted in figure 5 for an exhaust-gas temperature of 1600° F and for two typical circumferential thermocouple locations: (1) thermocouples between air-admission holes, and (2) thermocouples in line with louvers. At an inlet-air temperature of 860° F, liner temperatures decreased with increasing distance from the fuel nozzle, while at an inlet-air temperature of 200° F, no consistent trend was observed.

Carbon Deposition

The effect of variations in combustor inlet-air temperature and pressure on carbon deposition at constant combustor temperature rise is shown in figure 6. In general, carbon deposition decreased with increasing inlet-air temperature. Accompanying this decrease in carbon deposition was a pronounced change in the nature of the deposits. At the low inlet-air temperatures, uniform, hard carbon deposits were found on the dome and sometimes in the first few inches of the liner. As inlet-air temperature was increased, the deposits became lighter and more sooty until, at an inlet-air temperature of 860° F, both liner and dome were generally very clean. Whatever carbon deposits were obtained at the elevated temperature were found in one or more large pieces which either adhered to the inner surface of the liner (at the upstream end) or had broken away from the liner surface and were found lying in the liner or in the downstream section of the combustor rig. The weights of the loose pieces of carbon which were found downstream of the combustor liner at the end of a test were not included in the weight of carbon deposits plotted in figure 6; however, their weights are indicated separately in the figure.

The data in figure 6 have been replotted in figure 7 to illustrate more clearly the effect of combustor-inlet pressure on carbon deposition. At an inlet-air temperature of 200° F (fig. 7(a)), total carbon deposition increased rapidly with increasing pressure. This effect decreased with increasing inlet-air temperature until at a temperature of 860° F no significant effect of inlet-air pressure on carbon deposition was observed. In figure 7(b), deposit weight is based on grams per unit weight of fuel burned. At an inlet-air temperature of 200° F, deposits increased with an increase in pressure from 35 to 60 pounds, then decreased as the pressure was further increased to 173 pounds; all pressures are in units of pounds per square inch absolute. For the other inlet-air temperatures, the deposits decreased, in general, with increase in pressure, except for the pressure range from 60 to 80 pounds per square inch absolute.

The effects of inlet-air reference velocity and combustor temperature rise or fuel-air ratio on carbon deposition at constant inlet-air pressure and temperature are shown in figures 8(a) and (b), respectively. The data show a moderate increase in carbon deposition with increase in reference velocity. On a basis of weight of carbon deposit per unit weight of fuel burned, the deposits varied only slightly with increases in velocity. Increase in combustor temperature rise or fuel-air ratio resulted in a slight increase in carbon deposits. On the basis of weight of deposits per unit weight of fuel burned, the deposits increased as the temperature rise was increased to 1165° F, then the deposits decreased with further increase in temperature rise.

Smoke Formation

The effects of variations in inlet-air parameters on smoke formation are shown in figure 9. At constant inlet-air pressure, velocity, and combustor temperature rise, smoke density increased rapidly with increasing air temperature, reached a maximum at an inlet-air temperature of 600° F, and then decreased (fig. 9(a)). This trend was observed at the two high-pressure conditions only; at the low-pressure condition the amount of smoke observed was insignificant at all values of inlet temperature. At constant inlet-air temperature, reference velocity, and combustor temperature rise, smoke density increased with increasing pressure (fig. 9(a)). This trend was consistent for all values of inlet-air temperature investigated. The magnitude of smoke-density values obtained in the various reference-velocity tests (fig. 9(b)) and combustor temperature-rise tests (fig. 9(c)) was too small to attach any significance to the trends.

Combustion Efficiency

The effect of variations in inlet-air conditions on combustion efficiency is shown in figure 10. For the range covered, combustion efficiency generally increased with increasing fuel-air ratio. The effect of reference velocity on combustion efficiency varied with inlet-air temperature. At an inlet-air temperature of 200° F, combustion efficiency decreased markedly with increasing reference velocity, while at an inlet-air temperature of 860° F, combustion efficiency was not significantly affected by velocity. Increases in inlet-air temperature, at constant pressure and velocity, increased combustion efficiency except at the low-velocity condition where higher efficiency was obtained at the low inlet-air temperature conditions. Increases in pressure, at constant inlet-air temperature and velocity, brought about slight increases in combustion efficiency, as shown by a comparison of figures 10(a) and (b).

Combustor Total-Pressure Loss

Combustor total-pressure losses are presented in figure 11, where the ratio of total-pressure drop to the reference velocity pressure $\Delta P/q_r$ is plotted against combustor-inlet to -outlet gas-density ratio. The combustor pressure-loss coefficient $\Delta P/q_r$ increased with increasing gas-density ratio and with increasing inlet-air pressure and reference velocity. Increases in inlet-air temperature resulted in a slight decrease in the pressure-loss coefficient.

DISCUSSION

Liner Wall Temperatures

A discussion of the effects of operating conditions on liner temperatures should be based primarily on heat-transfer considerations. Thus, neglecting conduction along the metal parts, the heat transferred to the liner by radiation from the flame and by convection from the hot gases must equal the heat lost by the liner by convection to the cooling air and by radiation to the outer shell. Variations in operating parameters may change one or more of these heat-transfer processes and thus affect liner temperatures.

As shown in figure 4, liner temperatures increased rapidly with increasing fuel-air ratio or exhaust-gas temperature at an inlet-air temperature of 860° F. This increase may be attributed to the effect of increased radiation from the flame to the liner resulting from the increase in flame volume. At an inlet-air temperature of 200° F, the increase in liner temperatures with increasing fuel-air ratio was much less pronounced and at two locations (thermocouples 2 and 7) liner temperatures tended to decrease with increasing fuel-air ratio. Since these two thermocouples were located closest to the fuel nozzle, the decrease in liner temperatures may have been the result of fuel wetting of the liner wall at those locations.

The decrease in liner temperatures with increasing velocity (fig. 4) may be attributed to increases in convective cooling. Heat transfer through convection increases with increasing velocity or mass air flow; hence both heating and cooling of the liner through convection should increase with increasing velocity. However, if it is assumed that the heat transfer by radiation from flame to liner does not change appreciably with velocity, then the convective cooling will assume a greater share of the total heat transfer and, hence, liner temperatures will be reduced.

The large increase in liner temperatures with increasing inlet-air temperatures (fig. 4) may be attributed to one or more of the following

factors: (1) the large decrease in temperature differential available for convective cooling at the 860° F inlet-air temperature conditions, (2) the decrease in convective heat-transfer coefficient resulting from decreases in mass air flows at the high inlet-air temperature, and (3) increases in radiant heat transfer that might be expected from increased flame temperatures.

These results have shown that the most significant effects on liner temperatures were produced by changes in inlet-air temperature and in fuel-air ratio. Because of the limited amount of data, no rigorous correlation of the effect of inlet-air parameters was possible, especially in view of the wide circumferential variations in liner temperature that have been shown to exist in this type of combustor (ref. 5). However, preliminary calculations have shown that radiant heat transfer from the flame to the liner should increase appreciably with increasing fuel-air ratio and inlet-air temperature and slightly with increasing pressure and with decreasing velocity or mass air flow; these calculations are, in general, consistent with the results obtained.

Insufficient information is available on the velocity and direction of flow at the various locations within the flame zone to explain the variation in liner temperatures with combustor length (fig. 5) in terms of heat-transfer factors. The only consistent trend was obtained at the high inlet-air temperature conditions, where liner temperatures decreased with axial distance from the nozzle. The data were obtained at two circumferential locations only and, as noted previously, large circumferential temperature variations can be expected in this combustor. Figure 5 does show, however, that at the high inlet-air temperature investigated, excessive liner temperatures were observed, particularly in the upstream end of the combustor. For satisfactory durability at these conditions, additional cooling would be required.

Carbon Deposition

One of the objectives of this investigation was to determine the effect on carbon deposition of combustor operation at high inlet-air pressures, temperatures, and velocities - conditions that might be encountered at high flight speeds and with high-pressure-ratio engines. Previous work (ref. 1) has shown that, at low inlet-air temperatures, carbon deposition increased rapidly with increasing pressure; this trend was substantiated in the present investigations (fig. 7(a)). However, the data in figure 6 indicate that when inlet-air temperature was increased, carbon deposition decreased to a point where the combination of high pressures and temperatures formed less carbon than the low-pressure, low-temperature conditions encountered with current-production engines at subsonic flight speeds. This trend may be attributed, to a large extent, to the effect of liner wall temperatures. It was shown

3603

CL-2 back

that, for an inlet-air temperature of 200° F, liner wall temperatures were generally less than 1000° F, while for an inlet-air temperature of 860° F, liner temperatures varied between 1000° and 2000° F. It appears, therefore, that as inlet-air temperature was increased, the combustor liner became too hot to allow carbon formation on the walls. Further substantiation of this idea may be found in the nature of the carbon deposits. At low inlet-air temperatures, carbon deposition was uniform in the dome and the upstream portion of the liner, indicating that carbon formation was a regular and reproducible phenomenon. At high inlet-air temperatures, both dome and liner were generally very clean and whatever carbon was found was concentrated in a few random locations which, possibly because of local cooling or the condition of the metal at those points, were conducive to carbon deposition. These results are consistent with those obtained in another investigation (ref. 6) where a similar liner had been covered with a ceramic coating for the purpose of increasing liner temperatures and thus reducing carbon deposition. In that investigation carbon deposits in an uncoated liner were distributed uniformly over the dome and the upstream area of the liner; the deposits on the coated liner, however, were concentrated in two locations on the liner where some of the coating had disintegrated, while the rest of the liner and the dome was clean.

The increase in carbon deposition with increasing velocity (fig. 8(a)) at constant inlet-air temperature, pressure, and temperature rise has been observed previously (ref. 1) and may be attributed primarily to the increased fuel flow accompanying the increase in velocity; the effect on carbon deposition of increase in fuel flow resulting from changes in the other parameters is discussed to a greater extent in reference 1. The effect of combustor temperature rise or fuel-air ratio on carbon deposition (fig. 8(b)) is not considered particularly significant because of the low magnitude of carbon deposits obtained. At the low-temperature-rise condition the fuel-flow rate was very low and the total amount of carbon deposited was too small to be reproduced accurately. As a result, the relation between combustor temperature rise and carbon deposits per unit weight of fuel burned might be somewhat exaggerated.

Smoke Formation

The effects of variations in inlet-air parameters on smoke density (fig. 9) exhibit two important trends. The increase in smoke density with increasing pressure (fig. 9(a)) has been observed many times (e.g., refs. 1, 2, and 7) and, according to reference 7, may be attributed to the decrease in the rate of diffusion and, hence, in the rate of mixing of fuel and air resulting from the increase in pressure. The increase in smoke density with increasing inlet-air temperature might be attributed to the enrichment of the primary combustion zone resulting from increased rates of fuel vaporization at the high inlet-air temperatures. The flame

temperature may also have been increased. As a result of these two factors, cracking and decomposition reactions conducive to smoke formation may have been greatly advanced. The decrease in smoke density at an inlet-air temperature of 860°F might be attributed to a change in the decomposition process of the fuel or to increased burning of the smoke as the result of the increased exhaust-gas temperature; the tests were conducted at a constant temperature rise of 1165°F so that, at an inlet-air temperature of 860°F , an average exhaust-gas temperature of 2025°F was obtained. The effects of variations in reference velocity (fig. 9(b)) and combustor temperature rise (fig. 9(c)) on smoke are not considered significant because of the small magnitude of smoke densities observed in these tests.

Combustion Efficiency

The attainment of high combustion efficiency for conditions of high inlet-air temperatures and pressures would not be expected to be as serious a problem as under subsonic, low-pressure-ratio flight conditions. The data presented in figure 10 essentially substantiate this conclusion; the data also indicate that combustion efficiency was largely dependent on inlet-air temperature. Thus, at an inlet-air temperature of 200°F , combustion efficiency decreased with increasing velocity and with decreasing pressure, trends which are commonly observed in turbojet combustors. However, at an inlet-air temperature of 860°F , the adverse effect of increased velocity on efficiency was minimized by the beneficial effect of high inlet-air temperature on the combustion process; as a result, combustion efficiency decreased very little with increasing velocity. The slight decrease in combustion efficiency with increasing temperature observed at the low-velocity condition would not normally be expected, and may be the result of low fuel-nozzle discharge pressures since, at constant inlet-air pressure and velocity, air mass flows and, hence, fuel flows decrease with increasing inlet-air temperature.

It is noted in figure 10 that combustion efficiency values slightly higher than 100 percent were obtained in a few cases. The errors are believed to be due to inadequate average temperature measurements caused by thermocouple errors, insufficient flow sampling, or lack of mass weighting of temperatures. Inadequate flow sampling, especially of the cold gases near the wall, appears to be the most likely source of error. As a result, absolute efficiency values must be considered to be, on the average, somewhat high. Relative efficiency values, however, are believed to be good and, hence, any observed trends are considered to be significant.

Liner Durability

Although the effects of variations in inlet-air parameters on structural durability of the liner were not investigated as such, certain conclusions can be derived from operating experience. At the low inlet-air temperature conditions, no liner failures were encountered and, in general, no serious liner deterioration was observed after as much as 15 hours of intermittent operation; average exhaust-gas temperature varied from about 1000° to 2000° F during that time. These operating conditions were, in general, not more severe than the conditions at which this combustor operates in a current engine, namely, inlet-air temperatures up to 450° F, pressures to 75 pounds per square inch absolute, reference velocities to 125 feet per second, and exhaust-gas temperatures to 1400° F. However, at inlet-air temperatures of 860° F, pressures of 176 pounds per square inch absolute, reference velocities of 130 and 170 feet per second, and exhaust-gas temperatures of approximately 2000° F, liner structural failures occurred after only short periods of operations. Holes were burned in different parts of the liner and the liner was frequently partially collapsed. A photograph of a typical liner failure is shown in figure 12.

Such failures can be attributed primarily to the high liner temperatures and the high pressure drops associated with the preceding operating conditions. Thus, it was shown that, for an inlet-air temperature of 860° F, liner temperatures generally varied between 1000° and 2000° F. Likewise the pressure differential across the combustor liner was high. Although the data presented in figure 11 indicate that the pressure-loss coefficient $\Delta P/q_r$ for this combustor was in the range of many current turbojet combustors, the pressure-loss coefficient increased with increases in velocity and pressure. In addition, the increases in velocity and pressure increased q_r and hence ΔP substantially. At the high-pressure condition, absolute pressure drops greater than 20 pounds per square inch were encountered, compared with approximately 5 pounds per square inch for this combustor at rated engine speed and static sea-level conditions. Thus, the combination of high liner temperatures and high pressure drops presents a serious liner durability problem that would demand drastic combustor design changes for supersonic flight applications.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effects of large variations in combustor-inlet pressures, temperatures, and velocities on liner temperature, carbon deposition, smoke formation, combustion efficiency, and liner durability in a single tubular combustor:

1. At constant inlet-air pressure and velocity, liner temperatures increased with increasing inlet-air temperatures; the increase in liner temperature was generally considerably greater than the increase in inlet-air temperature. In comparison, the effects of other inlet-air variables were minor.

At an inlet-air temperature of 860° F, liner temperatures varied between approximately 1000° and 2000° F and increased with increasing fuel-air ratio. At an inlet-air temperature of 200° F, liner temperature varied between approximately 200° and 1000° F, but exhibited no consistent trend with changes in fuel-air ratio.

2. Total carbon deposition generally decreased with increasing inlet-air temperature. At low inlet-air temperatures, carbon deposition increased rapidly with increasing pressure; at high inlet-air temperatures, carbon deposits were small over the entire range of pressures.

At low inlet-air temperatures, carbon deposition was uniform in the dome and the upstream end of the liner; at high inlet-air temperatures, the dome and liner were generally very clean and whatever carbon was formed under those conditions was found in one or more isolated places in the upstream end of the combustor.

3. Smoke density increased as inlet-air pressure was increased and as inlet-air temperature was increased from 200° to 600° F; further increases in inlet-air temperature decreased smoke density.

4. At an inlet-air temperature of 200° F, combustion efficiency decreased noticeably with increasing velocity and with decreasing pressure; at an inlet-air temperature of 860° F, combustion efficiencies were appreciably higher and the effects of pressure and velocity on combustion efficiency were considerably smaller.

5. Operation of the combustor at high inlet-air temperatures, pressures, and velocities resulted in frequent liner failures due to extreme warping and burn-outs.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 26, 1955

3603

REFERENCES

1. Wear, Jerrold D., and Butze, Helmut F.: Preliminary Investigation of the Performance of a Single Tubular Combustor at Pressures up to 12 Atmospheres. NACA RM E53K09, 1954.
2. Butze, Helmut F.: Effect of Inlet-Air and Fuel Parameters on Smoking Characteristics of a Single Tubular Turbojet-Engine Combustor. NACA RM E52A18, 1952.
3. Topper, Leonard: Radiant Heat Transfer from Flames in a Single Tubular Turbojet Combustor. NACA RM E52F23, 1952.
4. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep 937, 1949. (Supersedes NACA TN's 1086 and 1655.)
5. Wilsted, H. D., Duffy, Robert T., and Grey, Ralph E.: Operating Temperatures of I-40-5 Turbojet Engine Burner Liners and the Effect of Temperature Variation on Burner-Liner Service Life. NACA RM E8F29, 1948. (Supersedes NACA MR E6E24.)
6. Butze, Helmut F., and Jonash, Edmund R.: Turbojet Combustor Efficiency with Ceramic-Coated Liners and with Mechanical Control of Fuel Wash on Walls. NACA RM E52I25, 1952.
7. Schalla, Rose L., Clark, Thomas P., and McDonald, Glen E.: Formation and Combustion of Smoke in Laminar Flames. NACA Rep. 1186, 1954. (Supersedes NACA RM's E51E15, E52G24, E52I26, E53E05, E53J12, and E54E03.)

TABLE I. - PHYSICAL PROPERTIES OF MIL-F-5624B,
GRADE JP-4 FUEL

Fuel properties	MIL-F-5624B, grade JP-4 (NACA fuel 52-288)
A.S.T.M. distillation, D86-46, °F	
Initial boiling point	139
Percentage evaporated	
5	224
10	253
20	291
30	311
40	324
50	333
60	347
70	363
80	382
90	413
Final boiling point	486
Residue, percent	1.2
Loss, percent	0.7
Aromatics, percent by volume	
A.S.T.M. D875-46T	10
Silica gel	10.1
Specific gravity	0.776
Viscosity, centistokes at 100° F	0.935
Reid vapor pressure, lb/sq in.	2.7
Hydrogen-carbon ratio	0.168
Net heat of combustion, Btu/lb	18,675
NACA "K" factor	278

TABLE II. - PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(a) Liner wall temperature tests.

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Combustor-inlet total pressure, lb/sq in. abs	57.7	57.7	57.3	57.7	57.7	58.2	57.8	57.8	57.8	58.2	57.8	57.8	58.2	58.2	58.0	57.8
Combustor-inlet temperature, °F	202	204	204	183	192	203	203	204	200	205	858	855	888	855	206	200
Air flow, lb/sec	4.40	4.40	4.43	4.44	4.43	8.22	8.28	8.22	8.28	8.26	4.08	4.07	4.04	4.09	10.65	10.69
Combustor-inlet reference velocity, ft/sec	70	70	71	70	70	131	132	132	132	132	129	129	128	129	172	172
Fuel flow, lb/hr	100	188	281	339	410	215	583	505	639	733	85	183	216	256	356	505
Fuel-air ratio	0.0063	0.0119	0.0178	0.0212	0.0257	0.0072	0.0129	0.0171	0.0215	0.0248	0.0058	0.0111	0.0148	0.0174	0.0093	0.0131
Mean combustor-outlet temperature, °F	875	1090	1506	1735	2025	720	1115	1410	1715	1910	1250	1608	1840	1975	840	1070
Combustion efficiency, percent	100.8	103.9	107.1	107.6	108.3	97.0	99.2	101.7	104.4	104.3	100.3	103.6	102.0	101.3	93.2	92.6
Fuel-nozzle capacity, gal/hr	60	60	80	80	60	60	60	60	80	60	60	80	80	60	110	110
Differential pressure across combustor, lb/sq in.	1.1	1.2	1.4	1.5	1.7	5.1	5.8	6.5	6.9	7.6	1.7	1.8	1.9	1.9	10.8	11.2
Liner temperature, °F, at thermocouple -																
1	415	300	250	240	275	255	235	230	225	230	1320	1285	1285	1185	285	245
2	900	850	890	450	450	540	585	480	420	400	1425	1870	2020	2015	380	375
3	345	420	420	365	390	280	280	275	280	290	1025	1200	1395	1470	245	235
4	440	585	810	575	595	350	405	410	430	445	1130	1395	1625	1750	325	330
5	480	890	775	770	825	415	525	545	585	615	1175	1480	1700	1865	385	430
6	490	705	870	900	1010	460	680	730	770	815	1045	1335	1515	1625	450	580
7	805	890	930	575	495	390	425	400	385	380	1195	1715	1855	1780	285	295
8	445	720	715	635	675	355	400	395	420	440	1115	1395	1640	1635	290	285
9	410	690	675	855	825	480	490	495	510	530	1080	1300	1540	1580	360	360
10	335	440	455	805	780	385	415	415	430	460	1055	1215	1360	1410	305	300
11	510	575	650	810	720	360	415	405	440	470	1220	1520	1710	1660	325	335
12	535	690	840	775	730	425	645	590	590	620	1235	-----	-----	-----	430	465
13	458	675	640	685	700	335	380	365	405	460	1140	1405	-----	-----	---	---
14	480	505	565	530	500	385	355	335	320	315	1475	1740	1910	1900	280	255

TABLE II. - Continued. PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR
(a) Concluded. Liner wall temperature tests

Run	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Combustor-inlet total pressure, lb/sq in. abs	88.0	88.2	175.8	176.2	175.8	176.8	175.4	175.4	175.4	176.8	175.4	176.2	176.2	177.0	175.8	175.8
Combustor-inlet temperature, °F	203	206	206	202	202	201	201	870	867	905	915	870	815	870	865	870
Air flow, lb/sec	10.70	10.76	13.80	13.35	13.28	13.45	13.23	6.74	6.72	6.73	6.73	12.58	12.40	12.37	12.58	12.48
Combustor-inlet reference velocity, ft/sec	172	173	71	70	70	70	89	71	71	72	73	132	125	129	132	131
Fuel flow, lb/hr	733	777	386	577	805	1002	1219	88	216	312	434	134	388	384	595	805
Fuel-air ratio	0.0190	0.0201	0.0075	0.0120	0.0168	0.0207	0.0258	0.0035	0.0089	0.0129	0.0179	0.0030	0.0087	0.0086	0.0131	0.0180
Mean combustor-outlet temperature, °F	1435	1630	770	1090	1425	1690	1895	1095	1455	1750	2030	1060	1390	1460	1750	2010
Combustion efficiency, percent	93.9	96.4	101.4	103.2	104.8	106.2	100.0	92.5	99.1	98.9	98.8	92.9	98.6	101.1	103.8	100.4
Fuel-nozzle capacity, gal/hr	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
Differential pressure across combustor, lb/sq in.	12.6	13.3	4.4	4.5	4.9	5.3	5.6	1.4	1.6	1.7	1.9	6.7	7.2	7.2	---	---
Liner temperature, °F, at thermocouple -																
1	245	240	255	225	225	255	280	1335	1485	1475	1440	1110	1180	1390	1370	1860
2	355	385	825	825	685	540	520	1335	1845	2035	2115	1180	1690	1725	1850	----
3	250	255	375	445	430	390	370	955	1170	1350	1500	925	1050	1075	1185	1350
4	355	360	460	665	670	590	535	1030	1335	1600	1845	975	1205	1270	1485	1735
5	415	305	335	435	510	550	540	1030	1370	1825	1960	920	1075	1120	----	----
6	680	710	640	790	1035	1180	1180	970	1235	1485	----	945	----	----	----	----
7	280	285	450	420	355	----	----	1025	1580	1585	1660	930	----	----	----	----
8	320	330	420	445	375	390	580	1025	1275	1425	1525	860	1070	1135	1250	1380
9	395	410	390	455	415	395	355	985	1195	1375	1550	950	1030	1100	1210	1445
10	325	280	305	400	415	375	380	955	1090	1230	1400	950	925	985	1000	1050
11	335	340	535	770	720	705	650	1120	1435	1665	1875	1050	----	----	----	----
12	485	485	545	680	685	620	590	1075	1405	1560	----	1000	1180	1280	1510	1710
13	----	----	----	----	----	----	----	----	----	----	----	1000	1200	1280	1475	1695
14	260	250	485	530	490	425	415	1230	1525	1840	----	1075	1240	1300	1420	----

TABLE II. - Continued. PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(b) Carbon-deposition tests

Run	Combustor-inlet total pressure, lb/sq in. abs	Combustor-inlet temperature, °F	Air flow, lb/sec	Combustor-inlet reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Combustion efficiency, percent	Fuel-nozzle capacity, gal/hr	Differential pressure across combustor, lb/sq in.	Run time, hr	Carbon deposited, g
33	35.1	190	2.93	75	174	0.0164	1365	102.4	21.5	1.5	2	3.2
34	35.1	400	2.32	79	140	.0168	1565	102.7	21.5	1.3	2	2.7
35	35.1	600	1.93	81	124	.0179	1765	99.2	21.5	.8	2	5.2
36	35.2	850	1.52	79	112	.0205	2025	91.4	21.5	1.1	2	.8
37	60.0	197	5.10	78	300	.0163	1365	102.5	40	2.1	2	12.2
38	60.0	200	5.13	78	293	.0159	1365	105.1	40	2.4	2	9.4
39	60.1	406	3.90	78	236	.0168	1565	102.0	40	1.4	2	4.2
40	60.0	600	3.14	77	208	.0182	1760	97.2	40	1.2	2	1.8
41	59.9	875	2.56	79	198	.0213	2035	87.4	40	1.1	2	^a 12.0
42	85.9	205	7.32	79	430	.0165	1360	101.4	60	2.9	3	17.7
43	85.7	404	5.67	79	340	.0167	1570	103.4	60	1.0	3	11.0
44	86.0	615	4.56	79	276	.0168	1770	104.7	60	1.6	3	5.5
45	86.0	865	3.65	78	248	.0189	2025	87.4	60	1.1	2.5	2.1
46	85.9	857	3.69	79	248	.0185	2025	89.8	60	1.8	2	8.0
47	85.9	405	9.38	132	565	.0167	1665	102.5	60	7.3	2	13.5
48	86.0	409	12.97	184	815	.0174	1570	98.6	110	18.0	2	16.4
49	85.9	405	5.62	79	214	.0106	1160	101.5	60	2.5	2	.9
50	85.9	403	5.65	79	510	.0251	1975	96.7	60	2.5	2	5.0
51	173.5	200	14.65	77	829	.0157	1340	103.6	110	7.0	3	23.0
52	173.2	195	14.70	77	835	.0157	1340	104.0	110	7.4	1	12.7
53	173.2	603	9.10	78	575	.0176	1765	100.9	60	4.1	2	1.4
54	173.1	855	7.32	77	491	.0186	2025	99.4	60	3.7	2	.5

^aIncludes 11.5 g found in exhaust section.^bIncludes 4.0 g found in exhaust section.

TABLE II. - Continued. PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(c) Smoke tests

Run	Combustor-inlet total pressure, lb/sq in. abs	Combustor-inlet temperature, °F	Air flow, lb/sec	Combustor-inlet reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Combustion efficiency, percent	Fuel-nozzle capacity, gal/hr	Differential pressure across combustor, lb/sq in.	Smoke density
55	35.2	196	2.94	76	174	0.0164	1370	102.4	21.5	1.3	0.03
56	35.2	393	2.43	82	155	.0177	1570	98.4		1.2	.02
57	35.1	600	1.91	80	123	.0179	1765	99.3		.7	.01
58	35.1	870	1.50	79	108	.0200	2030	92.4		.5	.05
59	85.8	200	7.51	80	468	.0173	1365	96.7		3.8	.07
60	85.8	408	5.56	78	153	.0076	915	92.2	60	2.3	.37
61	86.2	408	5.59	78	207	.0103	1080	92.4		2.3	.08
62	86.2	402	5.60	78	300	.0149	1365	94.1		2.4	.19
63	86.6	400	5.60	77	364	.0181	1580	97.0		2.4	.14
64	86.2	400	5.60	78	453	.0225	1795	94.3		2.5	.01
65	86.2	400	5.60	78	546	.0271	2090	97.2	110	2.6	.39
66	88.2	400	5.60	78	450	.0223	1790	94.5		2.5	.29
67	86.2	400	5.56	77	156	.0078	905	90.0		2.1	.40
68	85.8	600	4.52	78	322	.0198	1770	90.8		1.8	.74
69	86.2	868	3.66	78	282	.0214	2040	87.7		1.4	.28
70	85.8	403	9.25	130	626	.0188	1565	91.9	110	7.4	.02
71	85.9	402	12.95	182	848	.0182	1565	94.9		14.9	.04
72	173.1	200	14.81	79	899	.0169	1365	99.2		6.5	.39
73	173.1	402	11.17	77	718	.0178	1565	96.8		4.7	.55
74	173.0	610	9.08	78	652	.0200	1765	89.0		3.8	.82
75	173.4	862	7.31	77	615	.0234	2045	81.6	60	3.1	.37

TABLE II. - Continued. PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(d) Combustion efficiency and pressure-drop tests

Run	Combustor-inlet total pressure, lb/sq in. abs	Combustor-inlet temperature, °F	Air flow, lb/sec	Combustor-inlet reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Combustion efficiency, percent	Fuel-nozzle capacity, gal/hr	Differential pressure across combustor, lb/sq in.
76	57.9	198	4.42	70	126	0.0079	780	99.6	60	1.7
77	57.5	198	4.40	70	188	.0119	1050	99.8		1.8
78	57.9	198	4.38	69	266	.0169	1375	100.2		1.9
79	57.9	200	4.44	70	350	.0219	1700	101.5		2.1
80	57.9	200	4.40	70	445	.0281	2020	99.1		2.4
81	57.5	203	8.18	132	233	.0079	720	88.3		6.5
82	57.5	202	8.17	132	357	.0121	995	90.7		7.5
83	57.5	201	8.17	131	457	.0155	1220	93.0		7.8
84	57.9	200	8.19	130	537	.0182	1425	97.2		8.4
85	59.9	195	8.17	129	693	.0236	1700	95.0		9.4
86	58.3	200	8.20	130	773	.0262	1855	95.4		10.4
87	57.9	199	10.56	169	339	.0089	720	79.2		14.1
88	57.9	200	10.50	168	500	.0132	1000	84.2		15.3
89	57.9	200	10.56	169	658	.0173	1280	89.2		17.0
90	58.3	200	10.56	168	792	.0208	1490	90.4		18.7
91	57.9	200	10.58	169	843	.0222	1560	90.3		19.2
92	57.5	846	2.37	75	50	.0059	1205	90.3		.6
93	57.9	865	2.38	76	89	.0104	1525	96.3		.7
94	57.9	864	2.38	77	125	.0146	1775	96.8		.8
95	57.5	865	2.38	76	157	.0183	2020	99.7		.8
96	57.5	858	4.08	130	71	.0048	1150	88.6		2.6
97	57.9	858	4.09	130	120	.0082	1365	93.0		2.7
98	57.5	857	4.09	130	170	.0116	1585	96.1		2.8
99	58.3	862	4.09	129	223	.0152	1800	96.3		2.9
100	57.5	865	4.09	131	283	.0192	2040	97.1		3.1

TABLE II. - Concluded. PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(d) Concluded. Combustion efficiency and pressure-drop tests

Run	Combustor-inlet total pressure, lb/sq in. abs	Combustor-inlet temperature, °F	Air flow, lb/sec	Combustor-inlet reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Combustion efficiency, percent	Fuel-nozzle capacity, gal/hr	Differential pressure across combustor, lb/sq in.
101	57.9	868	5.29	170	56	0.0029	1040	85.0	60	4.6
102	57.5	863	5.28	170	129	.0068	1280	91.3		4.9
103	57.5	865	5.28	170	187	.0098	1480	94.5		5.2
104	57.9	860	5.33	170	246	.0128	1660	95.8		5.4
105	57.9	856	5.29	168	292	.0153	1805	96.3		5.4
106	57.5	858	5.29	169	344	.0181	1955	95.8	110	5.6
107	176.1	206	13.50	71	350	.0072	730	98.2		5.4
108	176.1	204	13.52	71	531	.0109	1010	102.4		5.8
109	176.1	202	13.43	70	723	.0150	1285	103.0		6.4
110	177.7	200	13.56	70	913	.0187	1535	104.0		6.7
111	176.5	200	13.47	70	1075	.0222	1770	105.4		7.0
112	176.1	200	13.47	70	1265	.0261	2000	104.9		7.3
113	176.1	204	24.70	130	763	.0086	805	95.2		20.0
114	175.3	203	24.74	131	1180	.0132	1105	95.4		----
115	174.5	203	24.59	131	1390	.0157	1270	96.8		----
116	176.9	872	6.75	71	102	.0042	1135	91.7		2.2
117	177.3	866	6.73	70	177	.0073	1350	98.7		2.2
118	176.1	866	6.73	70	246	.0102	1540	100.5		2.3
119	176.1	856	6.70	70	340	.0141	1765	99.7		2.4
120	176.1	853	6.66	69	443	.0185	2015	99.4		2.4
121	175.7	869	12.39	130	153	.0034	1080	89.6		8.6
122	176.1	860	12.39	129	343	.0077	1360	97.0		9.2
123	174.5	862	12.38	131	489	.0110	1560	96.7		9.8
124	175.3	866	12.38	130	630	.0141	1770	99.0		10.1
125	176.9	865	12.38	129	810	.0182	1990	97.8		10.5

TABLE II. - Continued. PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(d) Combustion efficiency and pressure-drop tests

Run	Combustor-inlet total pressure, lb/sq in. abs	Combustor-inlet temperature, °F	Air flow, lb/sec	Combustor-inlet reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Combustion efficiency, percent	Fuel-nozzle capacity, gal/hr	Differential pressure across combustor, lb/sq in.
76	57.9	198	4.42	70	126	0.0079	780	99.6	80	1.7
77	57.5	198	4.40	70	188	.0119	1050	99.8		1.8
78	57.9	198	4.38	69	266	.0169	1375	100.2		1.9
79	57.9	200	4.44	70	350	.0219	1700	101.5		2.1
80	57.9	200	4.40	70	445	.0281	2020	99.1		2.4
81	57.5	203	8.18	132	233	.0079	720	88.3		6.5
82	57.5	202	8.17	132	357	.0121	935	90.7		7.5
83	57.5	201	8.17	131	457	.0155	1220	95.0		7.8
84	57.9	200	8.19	130	537	.0182	1425	97.2		8.4
85	59.9	195	8.17	129	693	.0236	1700	95.0		9.4
86	58.3	200	8.20	130	773	.0262	1855	95.4		10.4
87	57.9	199	10.56	169	339	.0089	720	79.2		14.1
88	57.9	200	10.50	168	500	.0132	1000	84.2		15.3
89	57.9	200	10.56	169	658	.0173	1280	89.2		17.0
90	58.3	200	10.56	168	792	.0208	1490	90.4		18.7
91	57.9	200	10.56	169	843	.0222	1560	90.3		19.2
92	57.5	846	2.37	75	50	.0059	1205	90.3		.6
93	57.9	865	2.38	76	89	.0104	1525	96.3		.7
94	57.9	864	2.38	77	125	.0146	1775	96.8		.8
95	57.5	865	2.38	78	157	.0183	2020	99.7		.8
96	57.5	858	4.08	130	71	.0048	1150	88.6		2.6
97	57.9	858	4.09	130	129	.0082	1385	93.0		2.7
98	57.5	857	4.09	130	170	.0116	1585	96.1		2.8
99	58.3	862	4.09	129	223	.0152	1800	96.3		2.9
100	57.5	865	4.09	131	283	.0192	2040	97.1		3.1

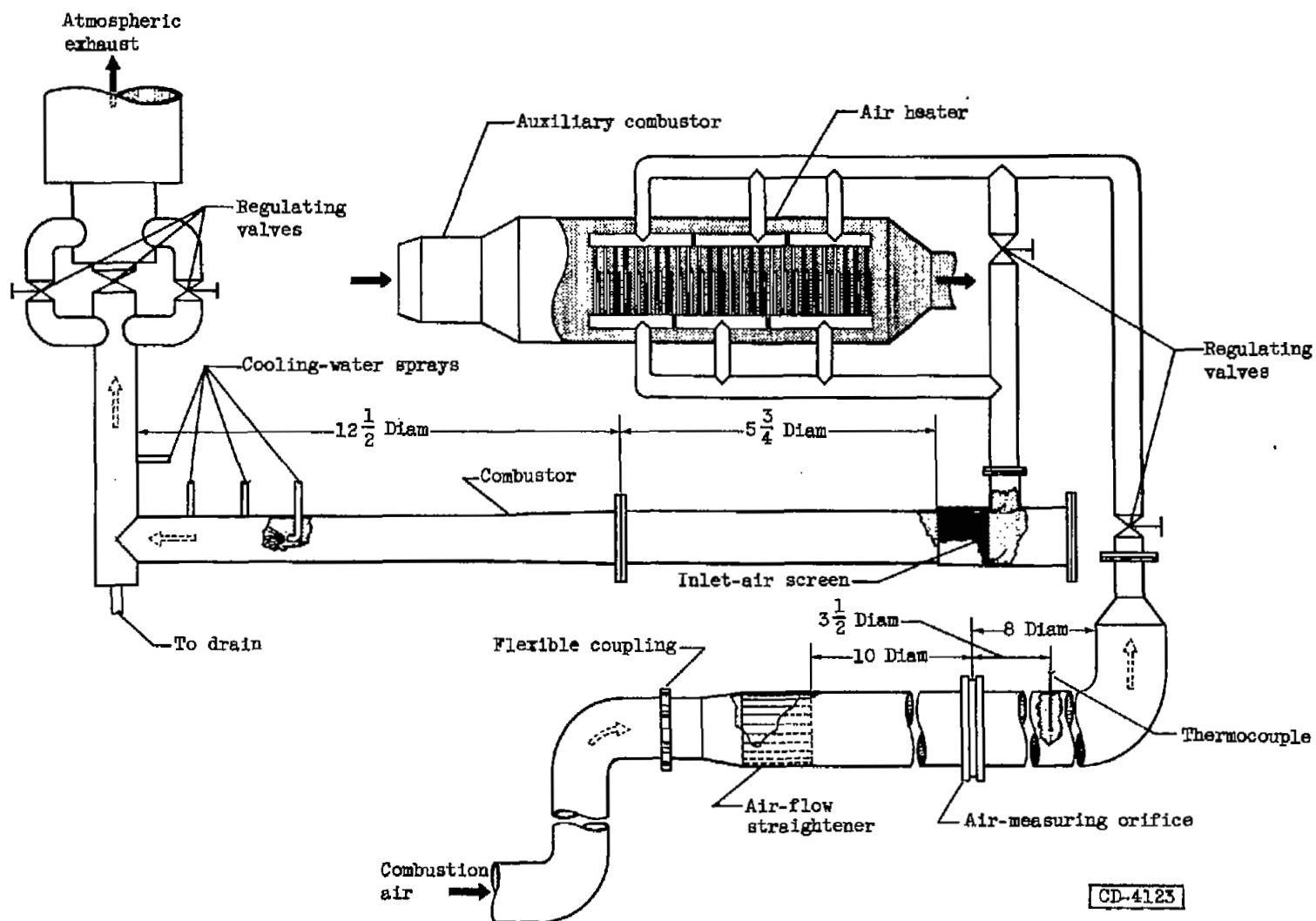


Figure 1. - Single-combustor installation and auxiliary equipment.

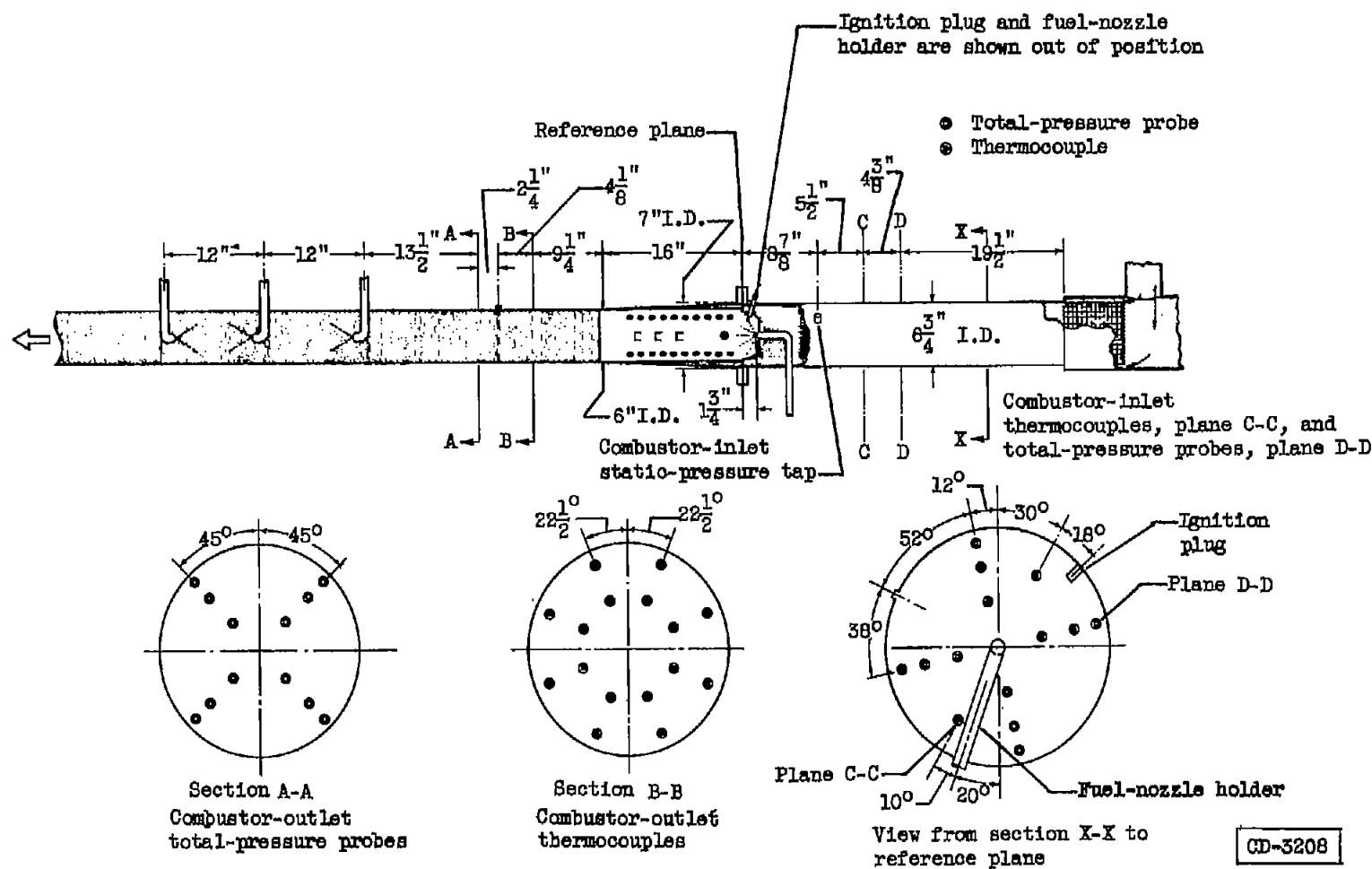
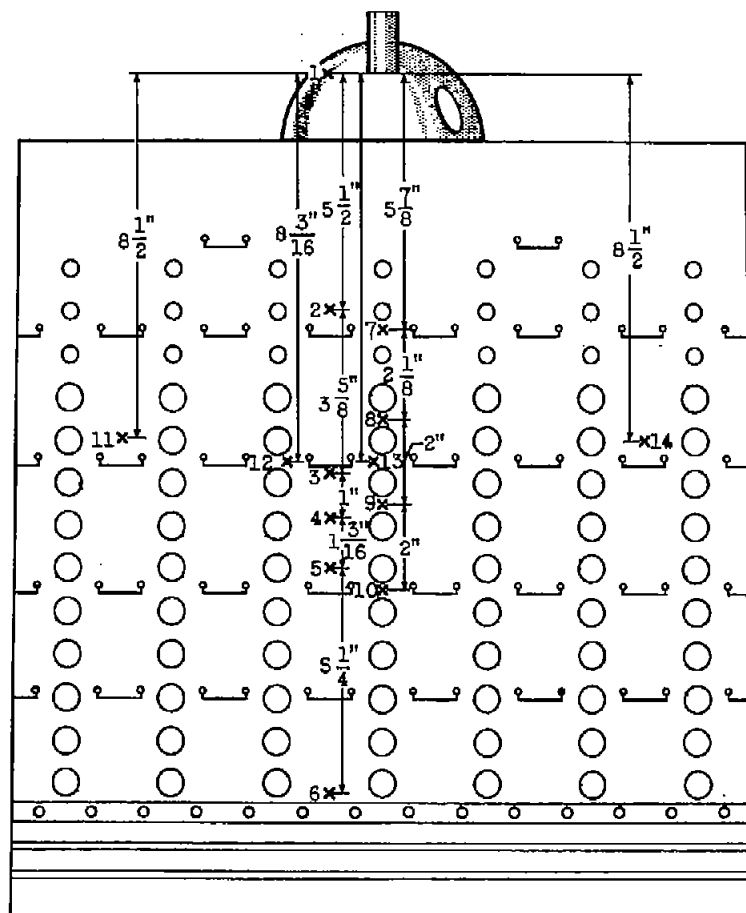


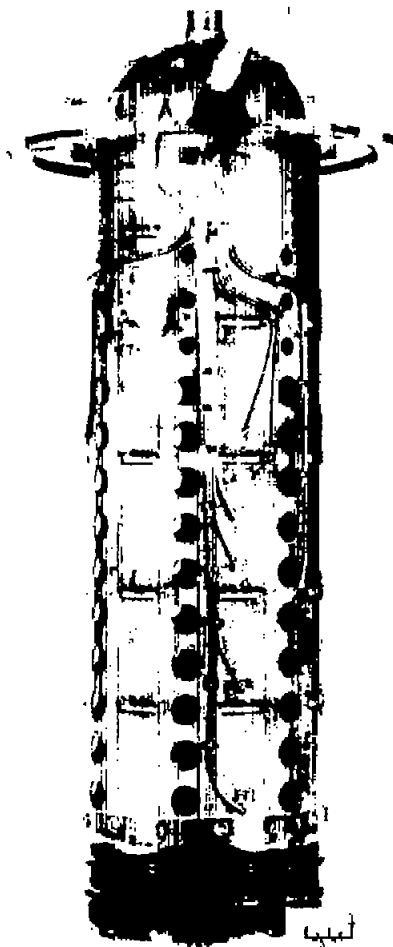
Figure 2. - Cross section of single-combustor installation showing auxiliary ducting and location of temperature- and pressure-measuring instruments in instrumentation planes.

X Thermocouple junction



(a) Developed view of liner.

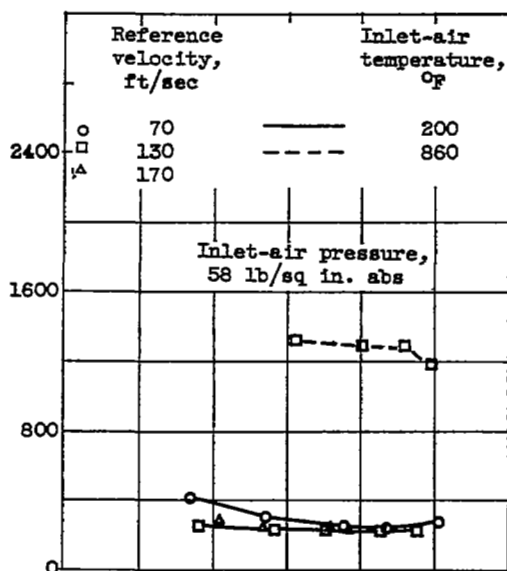
CD-4067



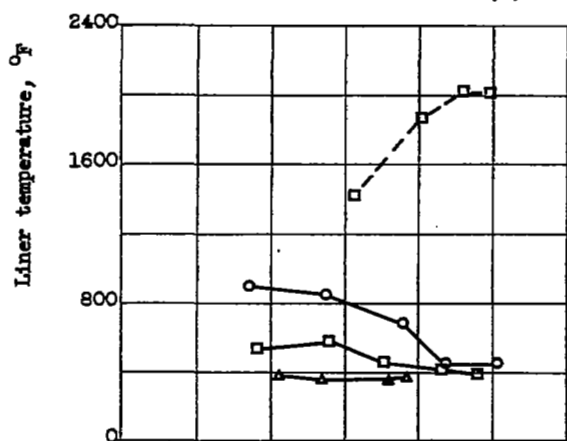
(b) Liner and dome.

C-34482

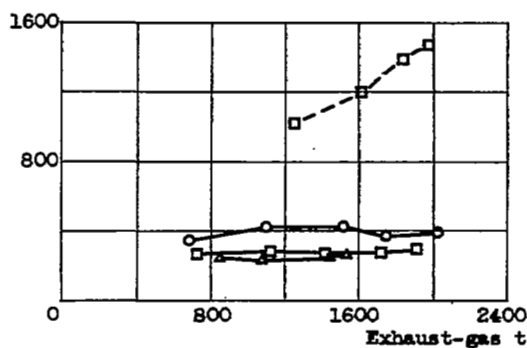
Figure 3. - Views of combustor liner showing thermocouple locations, designations, and method of installation.



(a) Thermocouple 1.

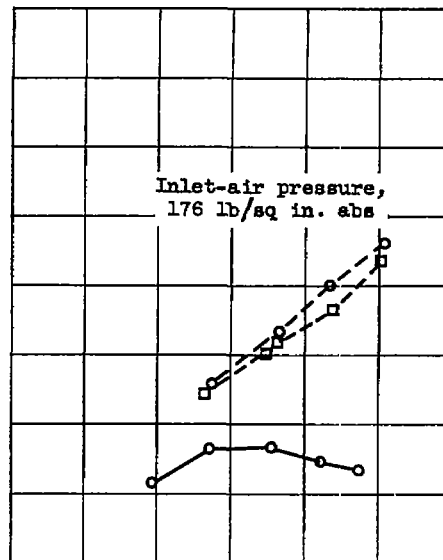
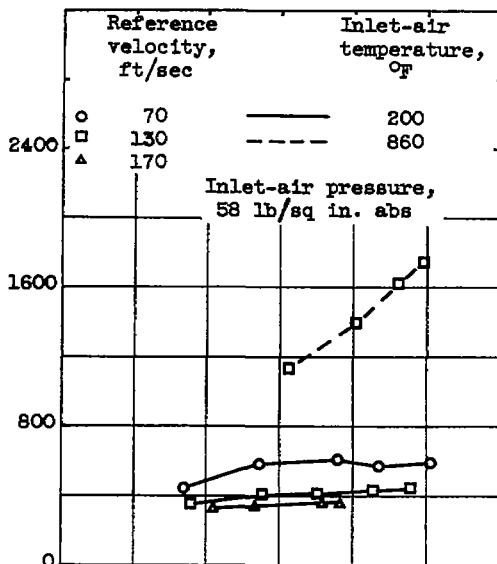


(b) Thermocouple 2.

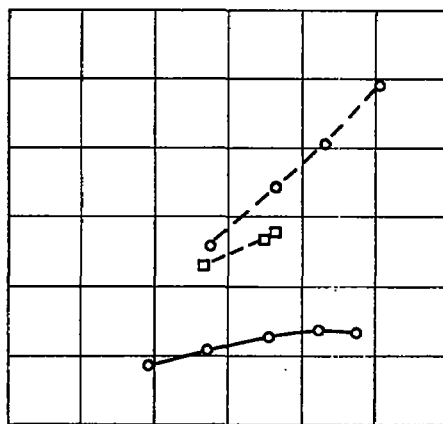
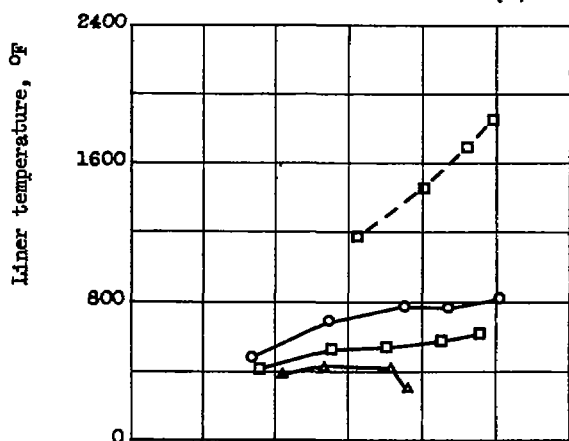


(c) Thermocouple 3.

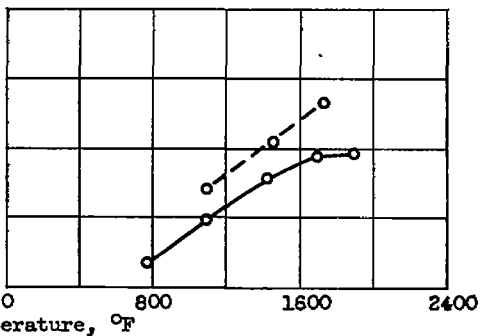
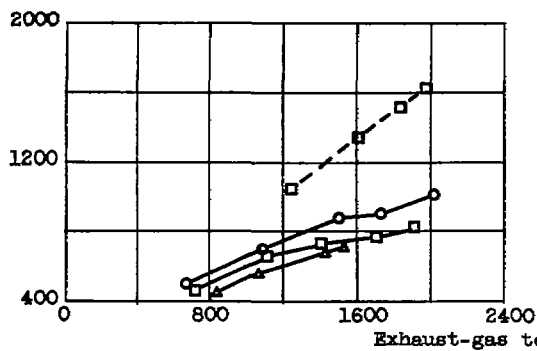
Figure 4. - Effect of operating conditions on liner temperatures.



(d) Thermocouple 4.

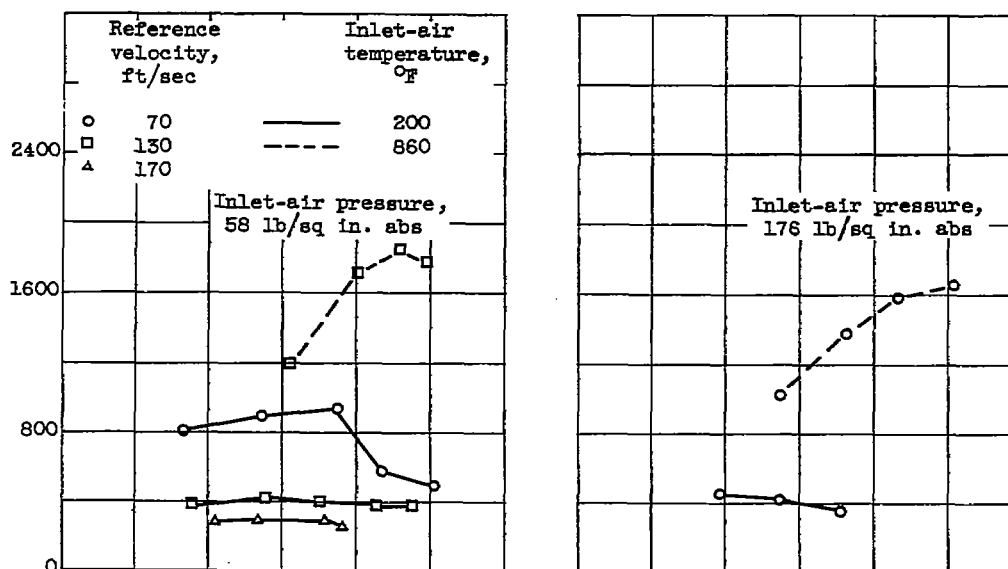


(e) Thermocouple 5.

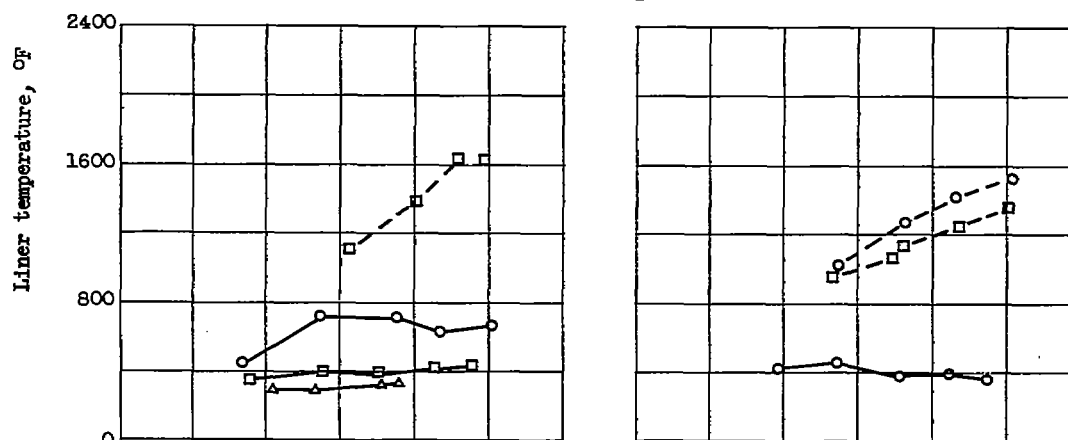


(f) Thermocouple 6.

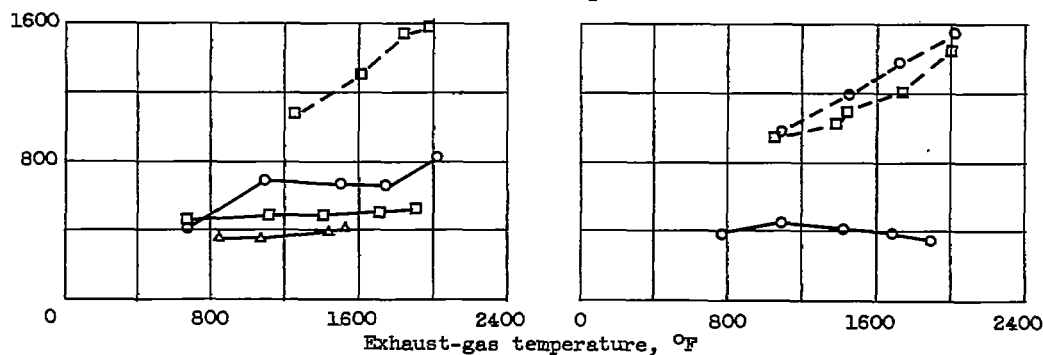
Figure 4. - Continued. Effect of operating conditions on liner temperatures.



(g) Thermocouple 7.

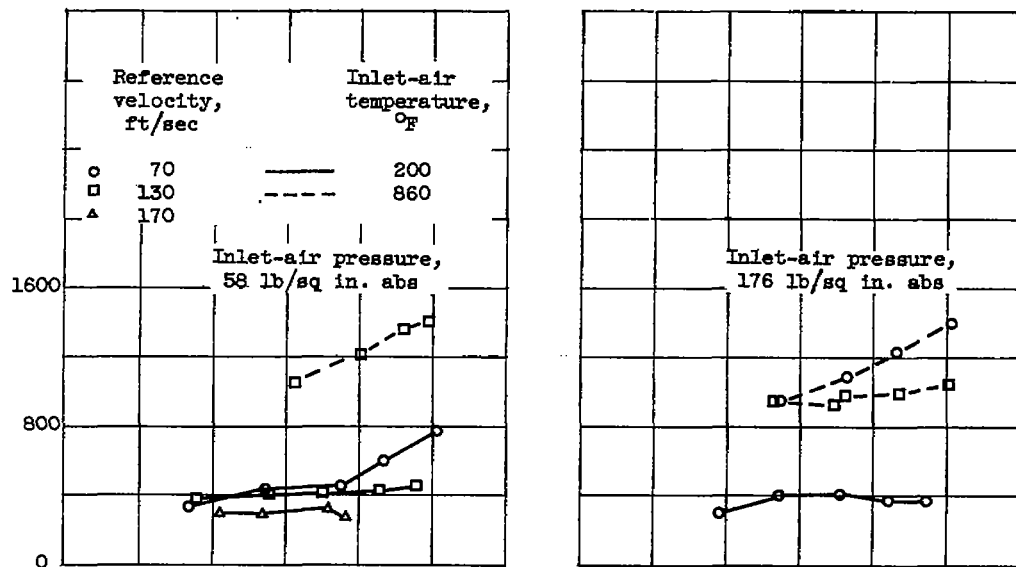


(h) Thermocouple 8.

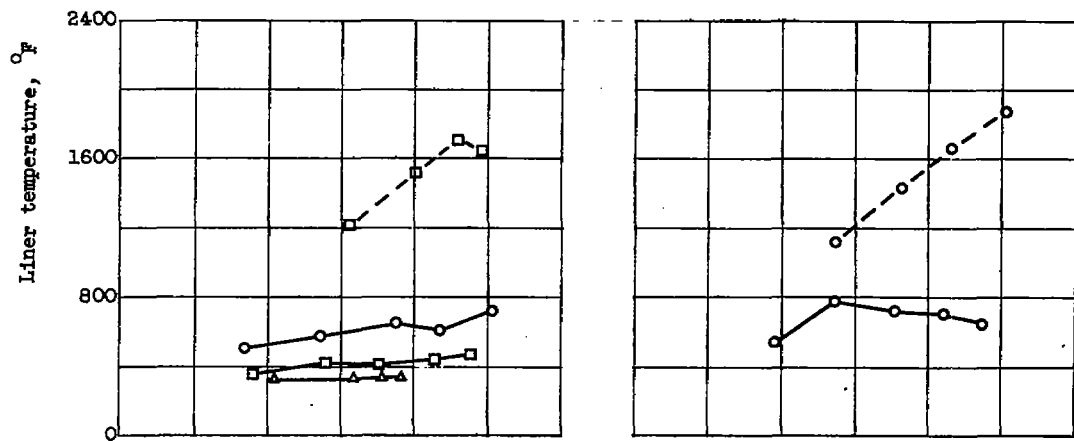


(i) Thermocouple 9.

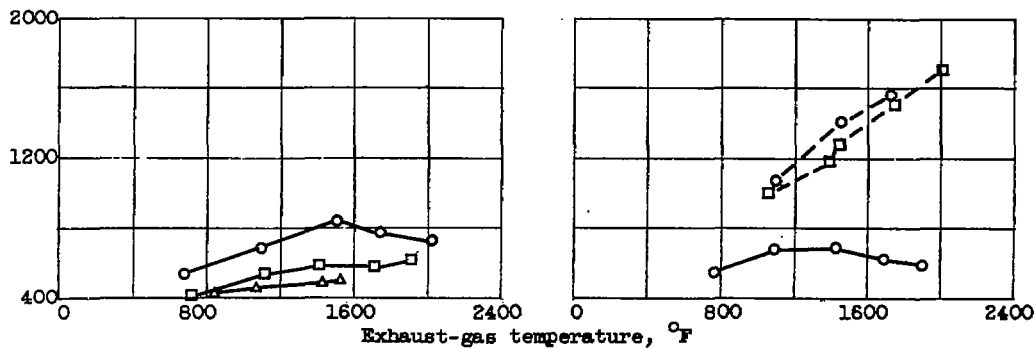
Figure 4. - Continued. Effect of operating conditions on liner temperatures.



(j) Thermocouple 10.



(k) Thermocouple 11.



(l) Thermocouple 12.

Figure 4. - Continued. Effect of operating conditions on liner temperatures.

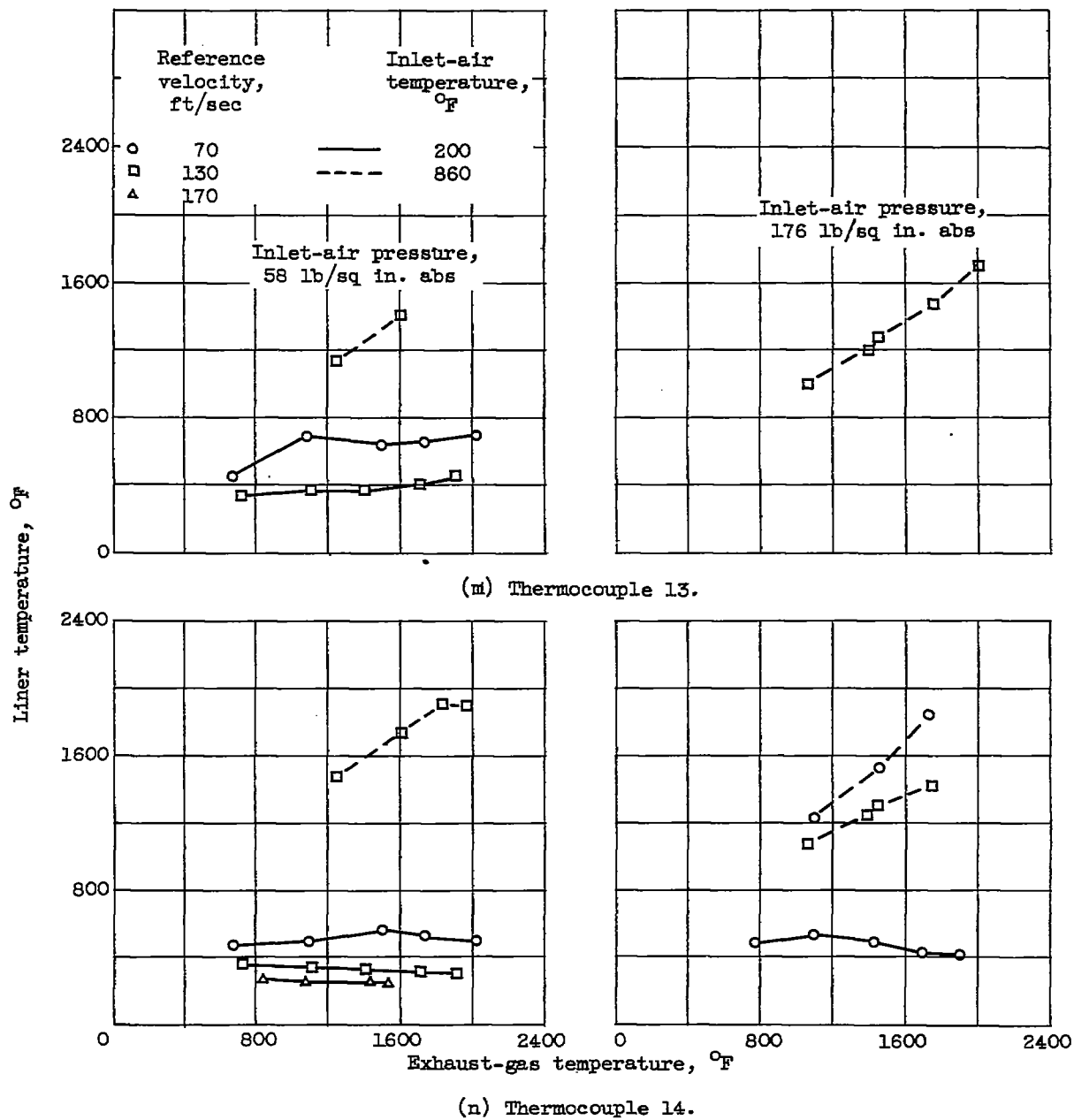
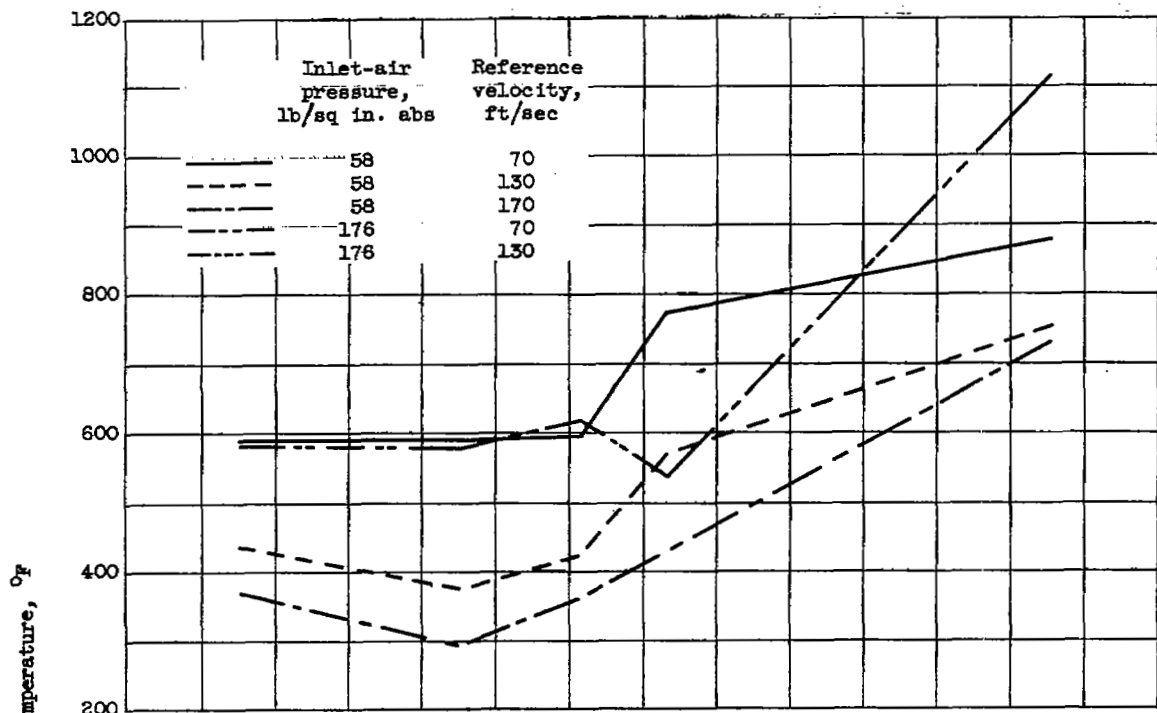
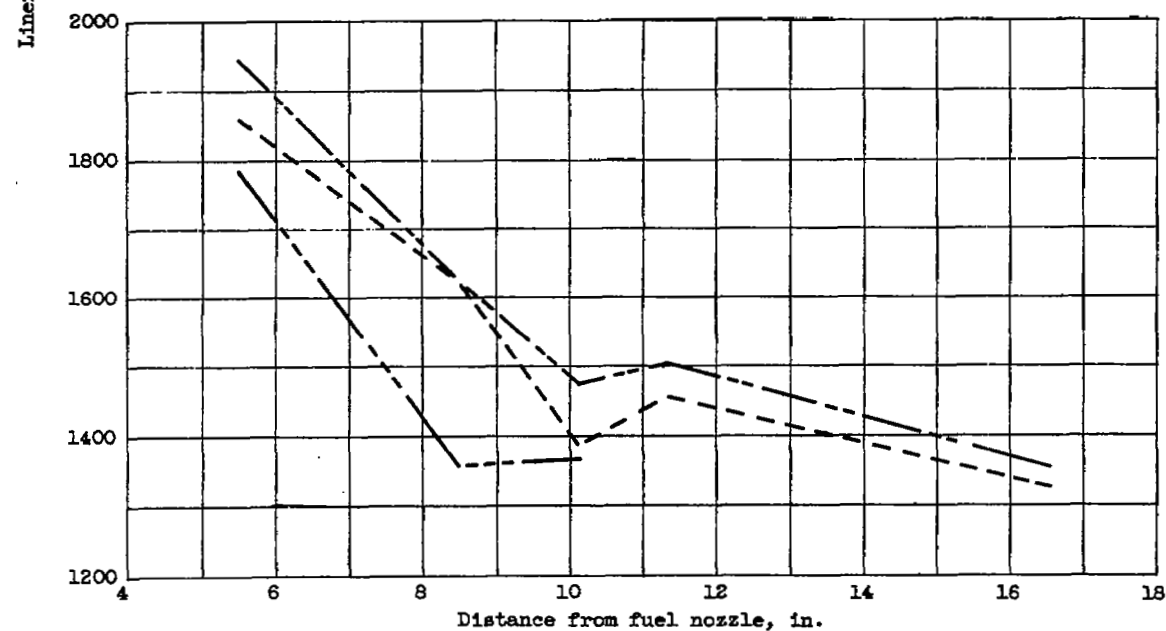


Figure 4. - Concluded. Effect of operating conditions on liner temperatures.

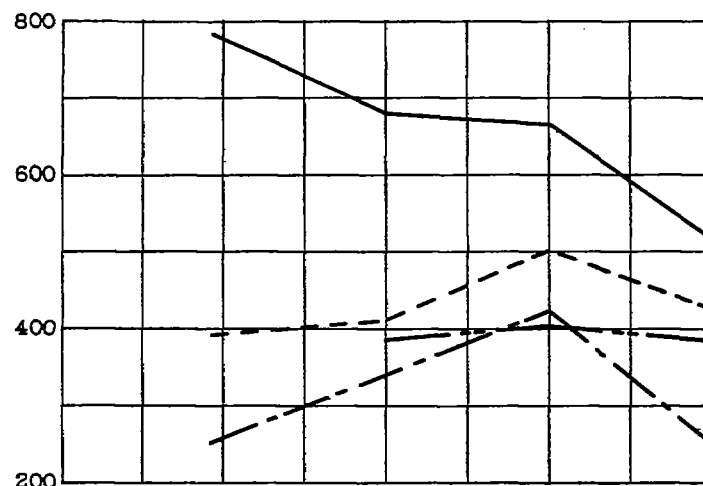


(a) Thermocouples in line with louvers; inlet-air temperature, 200° F.

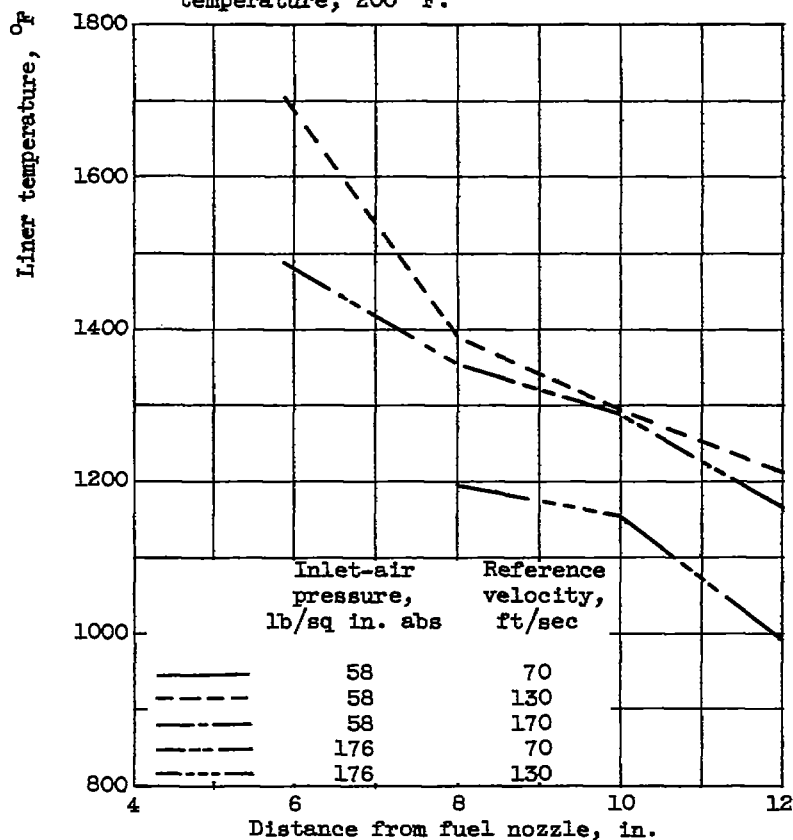


(b) Thermocouples in line with louvers; inlet-air temperature, 860° F.

Figure 5. - Effect of axial distance on liner temperatures. Exhaust-gas temperature, 1600° F.



(c) Thermocouples between air holes; inlet-air temperature, 200° F.



(d) Thermocouples between air holes; inlet-air temperature, 860° F.

Figure 5. - Concluded. Effect of axial distance on liner temperatures. Exhaust-gas temperature, 1600° F.

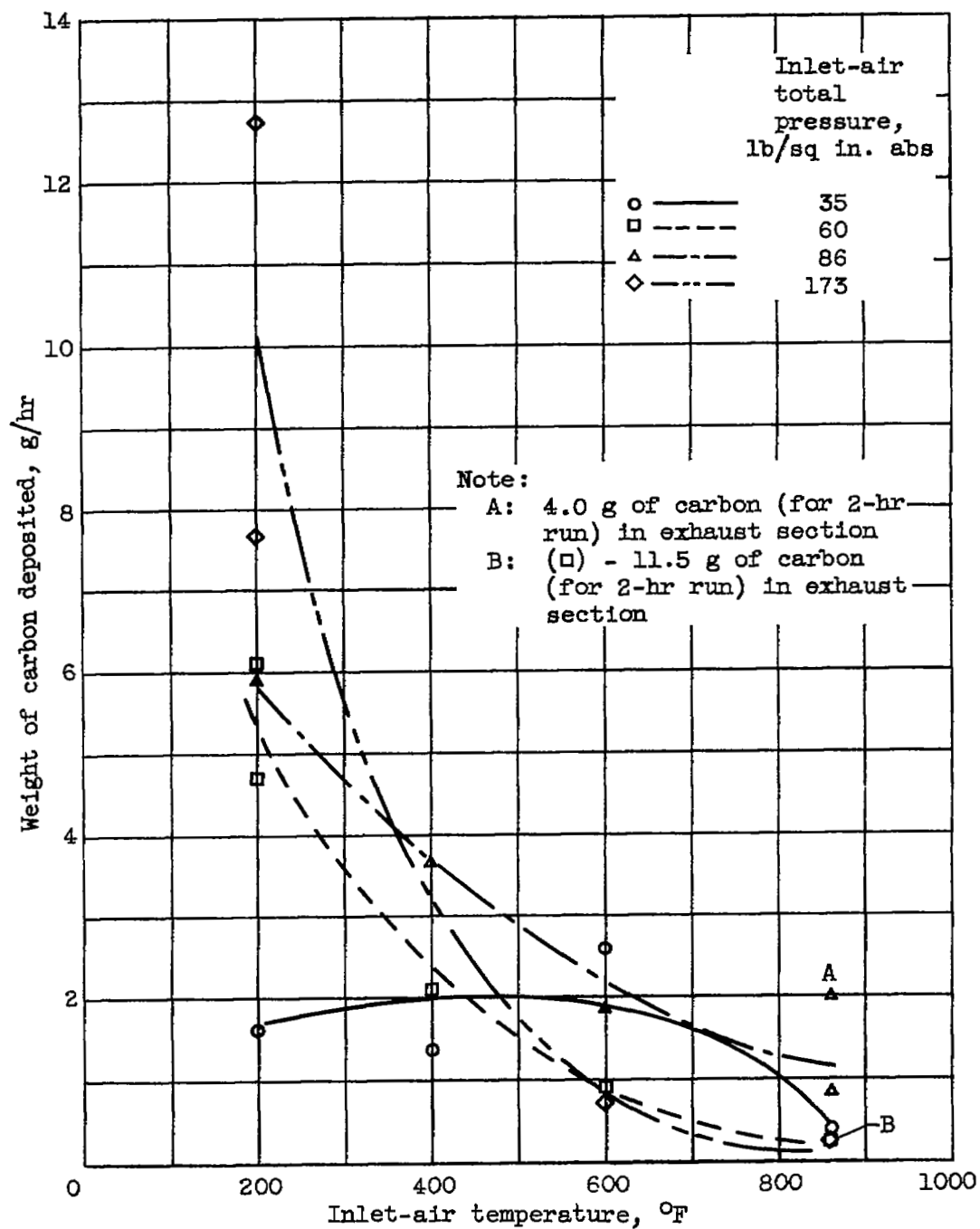
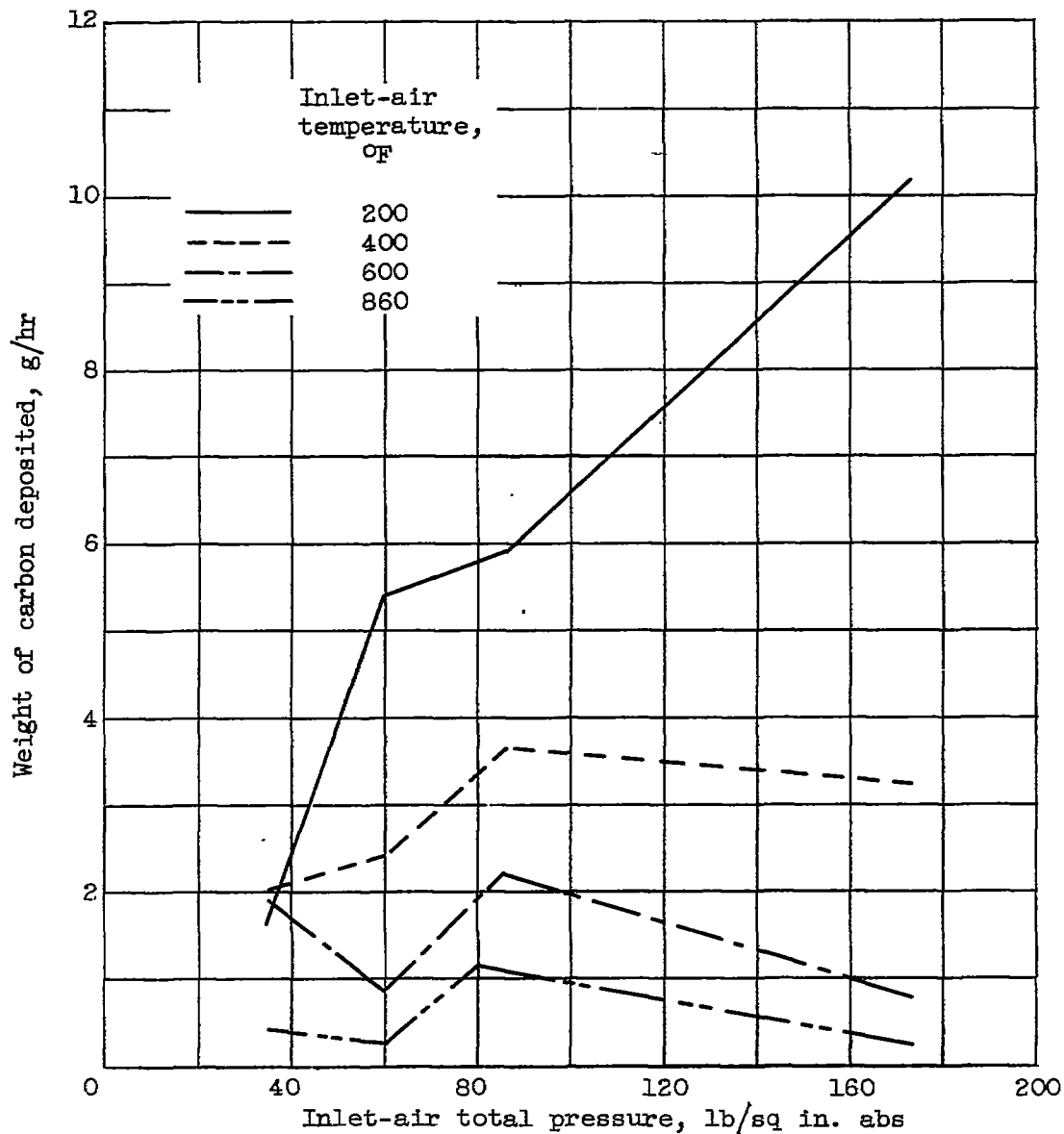
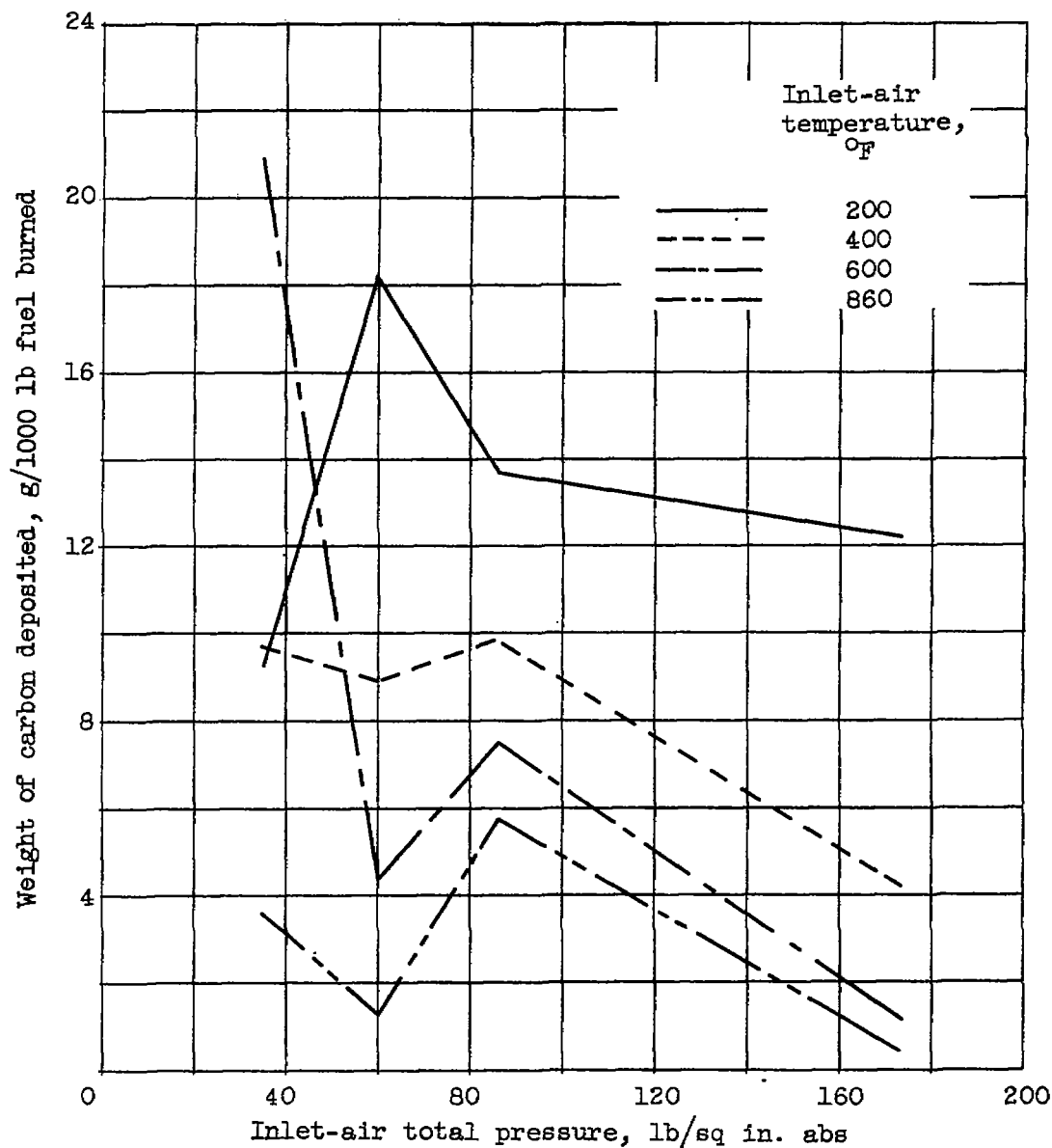


Figure 6. - Effect of inlet-air temperature on carbon deposition. Inlet-air reference velocity, 78 feet per second; combustor temperature rise, 1165° F.



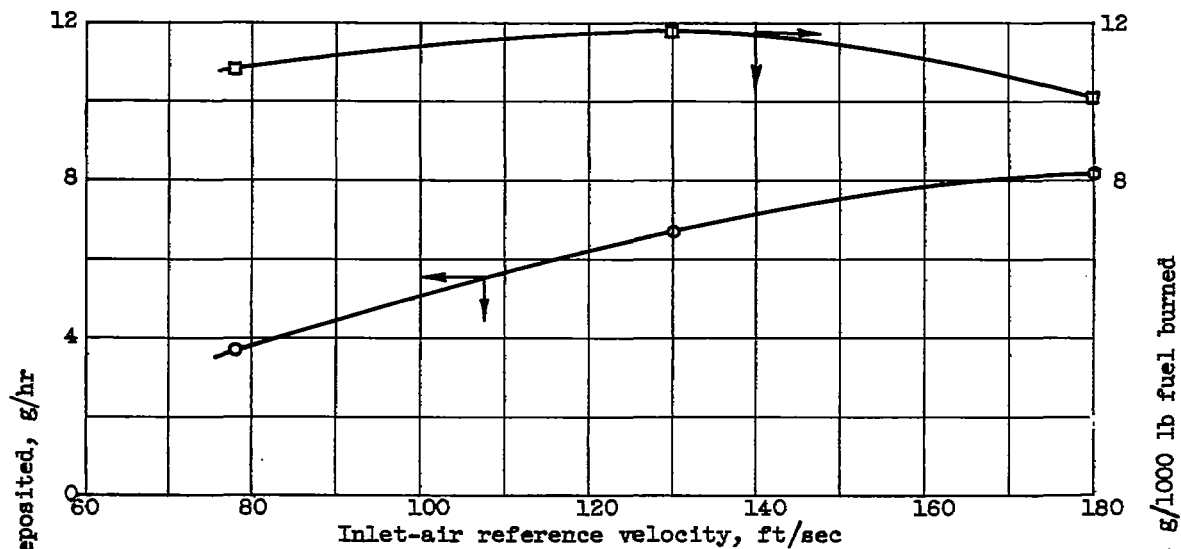
(a) Carbon deposit on basis of grams per hour.

Figure 7. - Effect of inlet-air total pressure on carbon deposition. Inlet-air reference velocity, 78 feet per second; combustor-temperature rise, 1165° F.

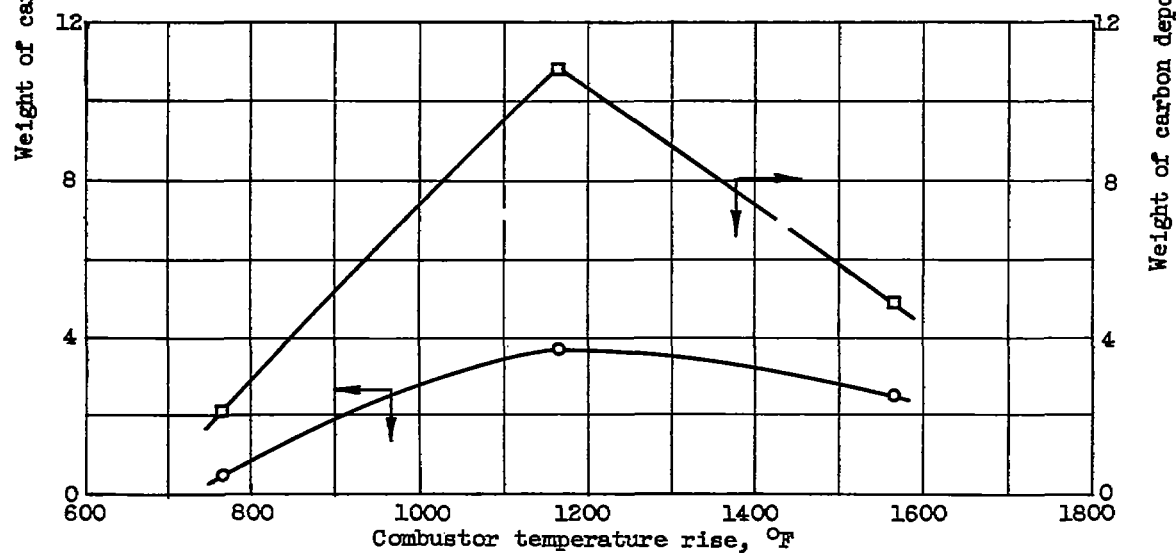


(b) Carbon deposit on basis of grams per 1000 pounds of fuel burned.

Figure 7. - Concluded. Effect of inlet-air total pressure on carbon deposition. Inlet-air reference velocity, 78 feet per second; combustor-temperature rise, 1165° F.

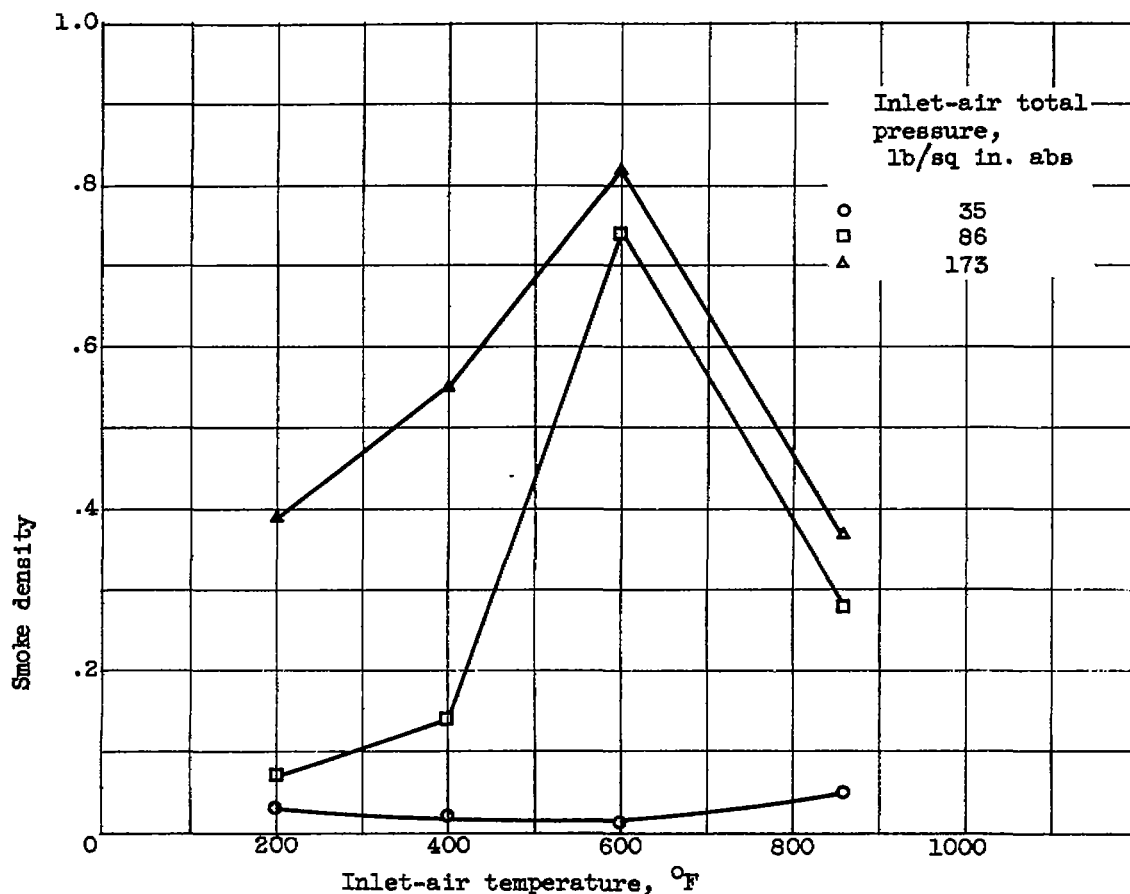


(a) Combustor temperature rise, 1165° F.

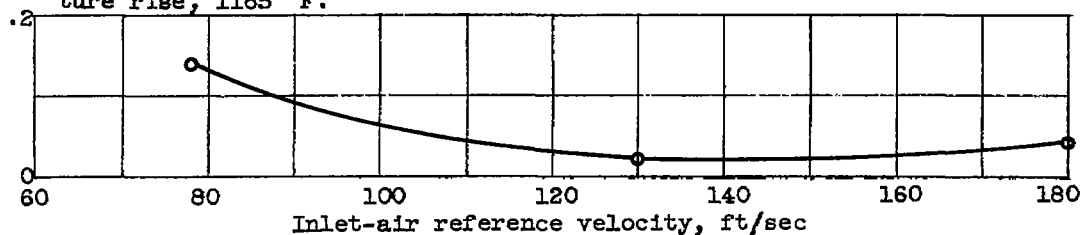


(b) Inlet-air reference velocity, 78 feet per second.

Figure 8. - Effect of combustor temperature rise and inlet-air reference velocity on carbon deposition. Inlet-air total pressure, 86 pounds per square inch absolute; inlet-air temperature, 400° F.

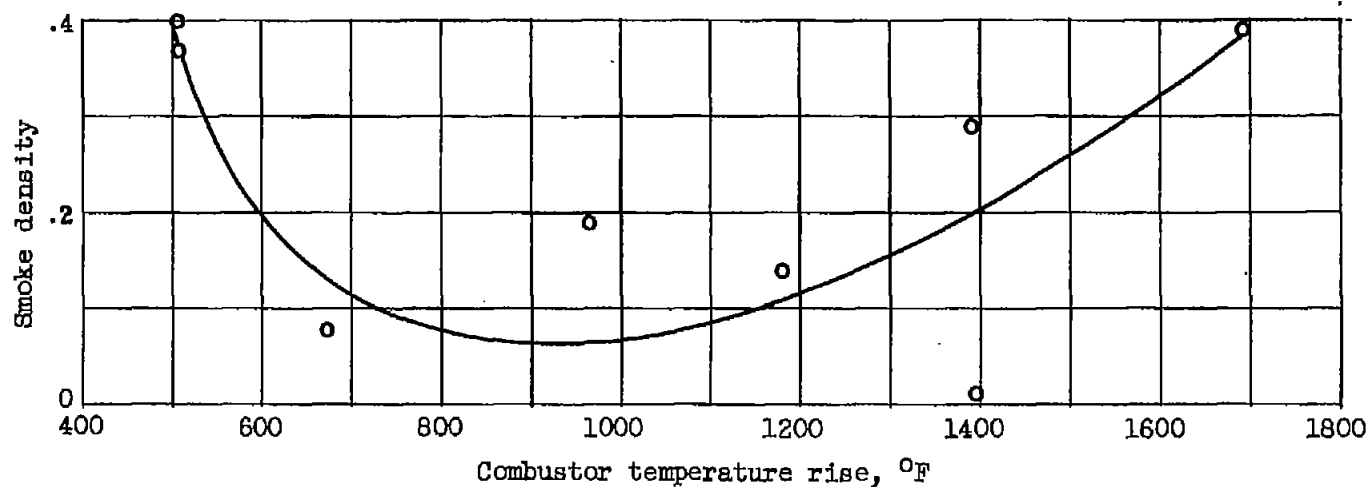


(a) Effect of inlet-air temperature and pressure. Inlet-air reference velocity, 78 feet per second; combustor temperature rise, 1165° F.



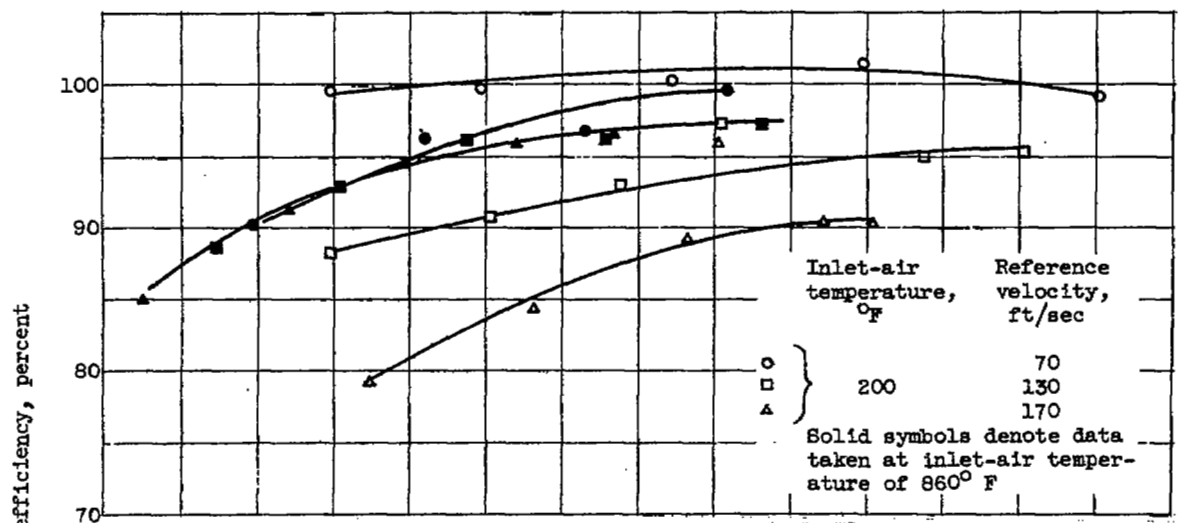
(b) Effect of inlet-air reference velocity. Inlet-air temperature, 400° F; inlet-air total pressure, 86 pounds per square inch absolute; combustor temperature rise, 1165° F.

Figure 9. - Effect of inlet-air conditions on smoke density.

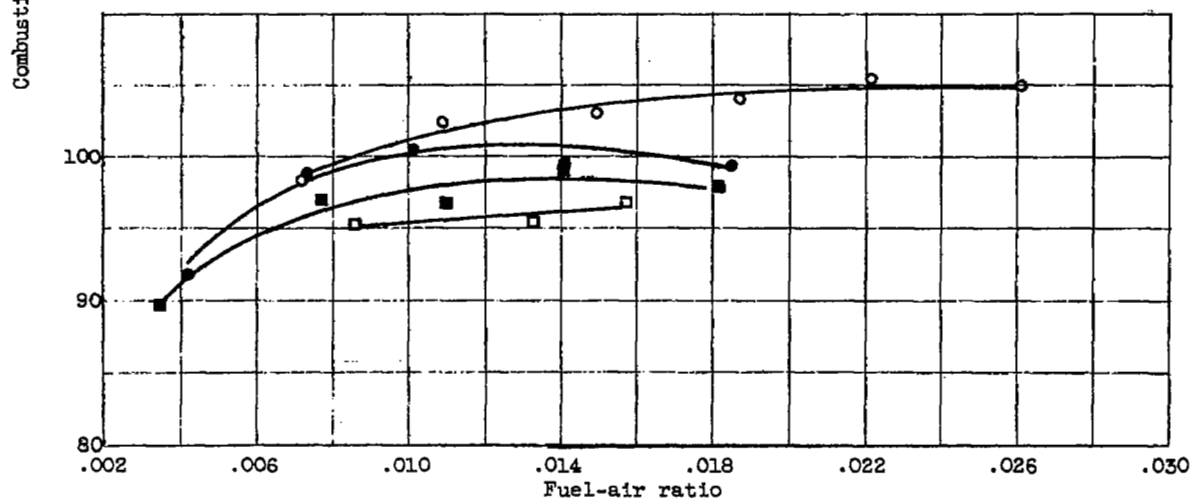


(c) Effect of combustor temperature rise. Inlet-air total pressure, 86 pounds per square inch absolute; inlet-air temperature, 400° F; inlet-air reference velocity, 78 feet per second.

Figure 9. - Concluded. Effect of inlet-air conditions on smoke density.



(a) Inlet-air total pressure, 58 pounds per square inch absolute.



(b) Inlet-air total pressure, 176 pounds per square inch absolute.

Figure 10. - Effect of inlet-air conditions on combustion efficiency.

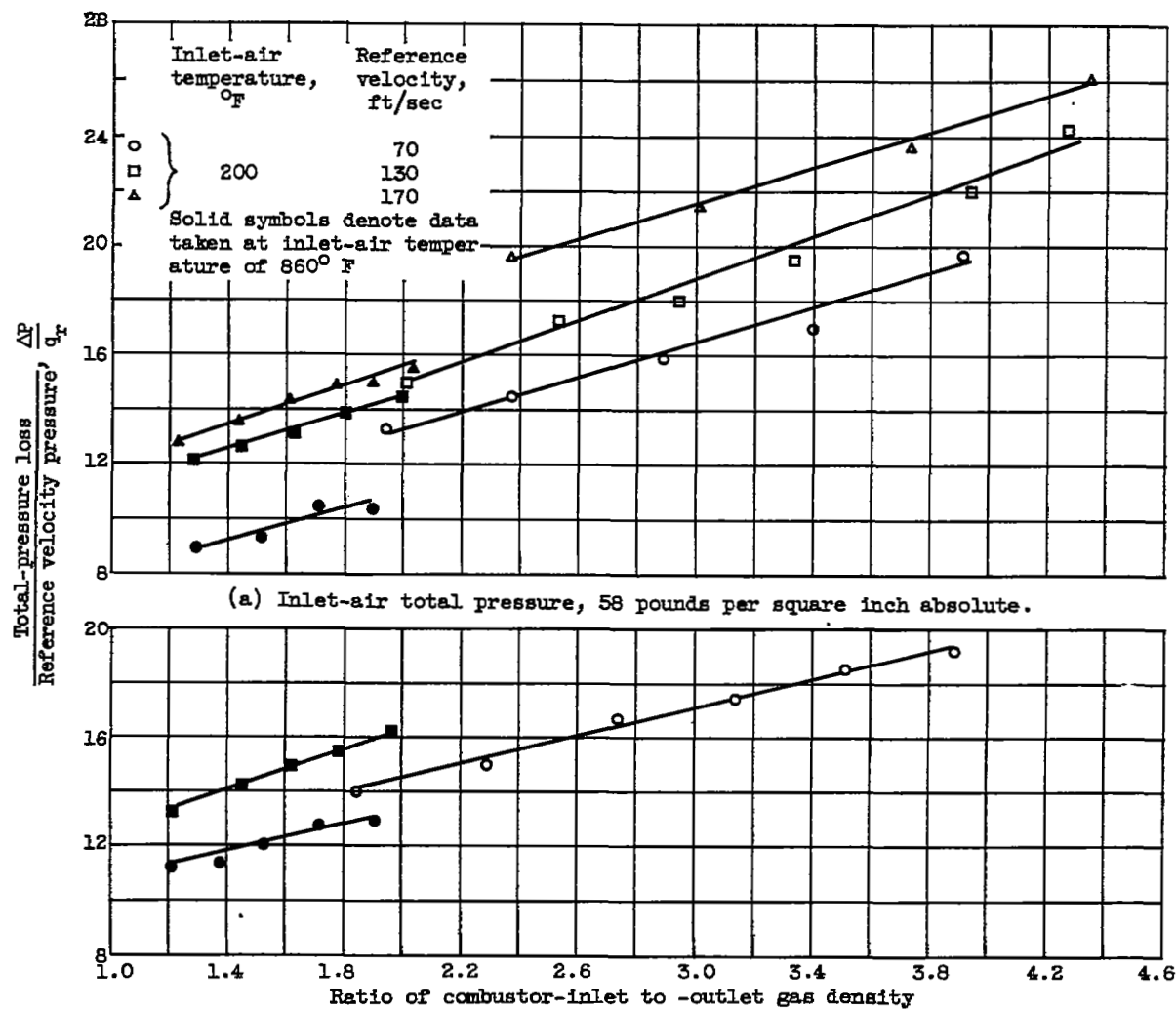


Figure 11. - Effect of inlet-air conditions on total-pressure drop.

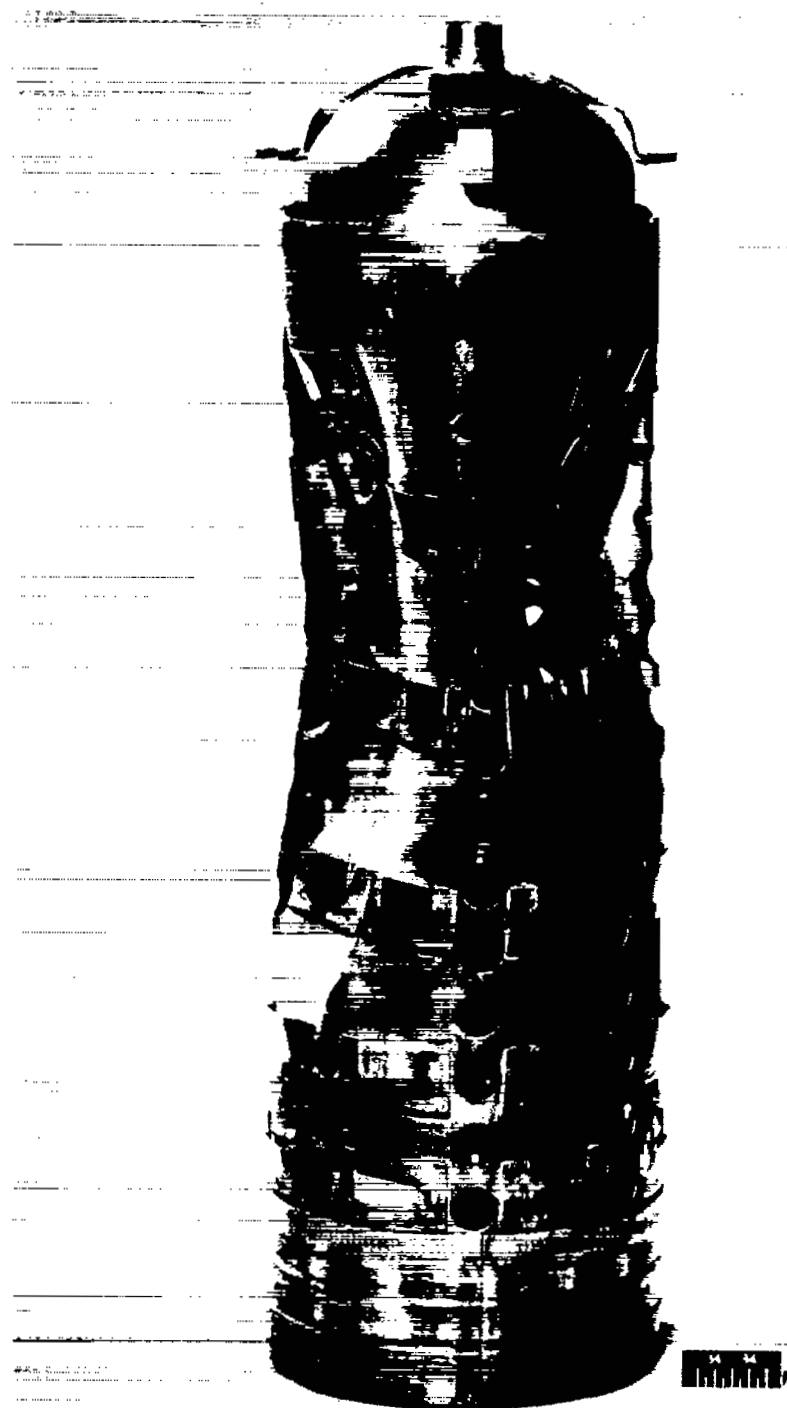


Figure 12. - Warped liner.

C-37045

[REDACTED]

NASA Technical Library
3 1176 01435 7991

[REDACTED]

[REDACTED]